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A measurement of correlation parameters in the decay of polarized free neutrons: the \textit{abBA} experiment

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Abstract. The \textit{abBA} experiment will measure, in the same apparatus, four correlation parameters in the free neutron $\beta$-decay: the electron-antineutrino angular correlation ($a$), the Fierz interference term ($b$), and the asymmetries, with respect to the neutron spin direction, of the electron ($A$) and antineutrino ($B$). The precise determination of these parameters, together with the neutron lifetime, will provide important information about the Standard Model (SM) and will establish constraints for new physics. In this paper we describe the experimental methodology of \textit{abBA} as well as some of the advances that have been done so far.

1. Introduction

The measurements pursued by \textit{abBA} will determine with high accuracy the $V_{ud}$ element of the Cabbibo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1, 2], whose nine matrix elements represent the transition amplitudes for weak processes. The accurate determination of the matrix elements is important for unitarity consistency checks of the matrix (weak universality), as well as to establish constraints to physics beyond the SM.

In the case of the unitarity of the top-row of the CKM matrix, where $V_{ud}$ is the most important element, for years the value of the sum $\sum_i |V_{ui}|^2$ was consistently between 2 and 2.5 $\sigma$ below unity, until recent re-measurements in $K$-decay resulted in a significant correction to the previous value of $V_{us}$ [3]. With the new value of $V_{us}$, unitarity with the first row seems now well established ($\sum_i |V_{ui}|^2 = 0.99990(60)$) [4], however uncertainties related to the total transition energy ($Q_{EC}$) in the superallowed nuclear $\beta$-decays from where the present value of $V_{ud}$ is obtained still remain, and must be resolved before a definitive confirmation of unitarity is possible [3, 4].

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In the superallowed beta-decays only the vector current is involved and therefore $G_V = G_F V_{ud}$, where $G_V$ is the neutron vector form factor and $G_F$ the Fermi coupling constant, which is well known from $\mu$-decay. The neutron lifetime ($\tau_n$) is also defined by the vector and axial-vector neutron form factors ($G_V$ and $G_A$), or can as well be expressed in terms of $V_{ud}$ and $\lambda$, where $\lambda$ is the ratio of axial-vector to vector neutron coupling constants ($g_A$ and $g_V$), which at the low momentum transfers that characterize the neutron $\beta$-decay are equivalent to the form factors ($\lambda = g_A/g_V = G_A/G_V$)

$$\tau_n = \frac{K}{G_V^2 + 3G_A^2} = \frac{K}{G_F^2|V_{ud}|^2(1 + 3\lambda^2)},$$

where $K$ is a constant [3]. From the expression above it can be noted that measurements of $\tau_n$ and $\lambda$ are required to determine the value of $V_{ud}$

$$|V_{ud}|^2 = \frac{K}{G_F^2\tau_n(1 + 3\lambda^2)}.\tag{2}$$

As noted before, at present the most precise determination of $V_{ud}$ comes from superallowed nuclear $\beta$-decays. Its extraction from free neutron $\beta$-decay, which would have the advantage of being unencumbered by many-nucleon effects present in other nuclear decays, has however not been as precise due to experimental inconsistencies in $\lambda$ and $\tau_n$. Neutron studies like $abBA$ are attempting to resolve these inconsistencies, potentially making the free neutron $\beta$-decay the most accurate way to determine $V_{ud}$.

There is a number of observables related to the neutron decay. The decay rate of polarized neutrons can be expressed in terms of these observables as follows:

$$\frac{d^3W}{dE_e d\Omega_e d\Omega_\nu} = \frac{G_F^2|V_{ud}|^2 p_e E_e (E_a - E_e)^2}{(2\pi)^3} \left[ 1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} \right] + \frac{\hat{\sigma}_n}{E_\nu} \left( B \frac{\vec{p}_\nu}{E_\nu} + A \frac{\vec{p}_e}{E_e} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right).\tag{3}$$

$D$ is the triple correlation coefficient (projection of $\hat{\sigma}_n$ perpendicular to the decay plane) and is not measured by $abBA$. In the vector minus axial-vector ($V - A$) frame of the SM, the four observables measured in $abBA$ depend only in one parameter, $\lambda$:

$$a = \frac{(1 - \lambda^2)}{(1 + 3\lambda^2)}, \quad b = 0,\quad B = \frac{2\lambda(\lambda - 1)}{(1 + 3\lambda^2)}, \quad A = -\frac{2\lambda(\lambda + 1)}{(1 + 3\lambda^2)}.\tag{4}$$

The relationships above manifest a very important aspect of the neutron $\beta$-decay: that it is overdetermined. From expression 3, at most three parameters are needed to describe the neutron $\beta$-decay in the SM: $\lambda$, $V_{ud}$ and $\phi$ (the relative phase between $g_A$ and $g_V$; parameter $D$ depends on both, $\lambda$ and $\phi$). However, a larger number of observables ($\tau_n$, $a$, $b$, $B$, $A$, $D$, etc.) are accessible. This overdetermination of the problem allows to perform different consistency checks of the SM and a sensitive search for new physics.

Parameters $a$, $B$ and $A$ have been measured experimentally to a precision of $10^{-3}$ [3]. Sensitivity estimations of the $abBA$ experiment, to be performed at the Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory (ORNL), indicate up to an order of magnitude improvement in these three parameters ($10^{-4}$ precision), and in the case of $b$, the first measurement ever in neutron decay [5].
2. Experimental methodology

The experiment will be performed at the new Fundamental Neutron Physics Beamline (FnPB) at the SNS. Figure 1 shows a scheme of a side view of a transverse cut of the experiment. A pulsed (60 Hz) neutron beam will be polarized either by the use of a $^3$He spin filter [6, 7] or by a supermirror polarizer [8]; the collaboration is at present evaluating both possibilities. Magnetic field coils provide a holding field for transport of the polarized neutron beam and an adiabatic RF spin flipper (SF) is used to control systematic effects. Neutrons will then be conducted into the decay region, an ultra-high vacuum 60 cm$^3$ volume defined entirely by magnetic fields so that neutrons do not interact with any matter. The original design of the experiment considered a symmetric decay spectrometer, at the center of which the decay volume is located, as shown in figure 1. The collaboration has recently worked out the new asymmetric spectrometer design for better control of the main systematic effects [9]. The spectrometer is a $4\pi$ detector sensitive to decay electron-proton coincidences.

![Figure 1. Representation of a side view transverse cut of the abBA experiment.](image)

The symmetric spectrometer, conceptually shown in figure 2, consists of cylindrically symmetric magnetic and electric fields whose intensities vary along the spectrometer axis as shown in figure 3, and two segmented silicon detectors at both ends for decay electrons and protons. The intense transverse magnetic field in the decay region (4 T) causes the decay protons and electrons to drift along the magnetic field lines with gyration radii of the order of 1 mm, despite the three orders of magnitude difference in their characteristic emission energies ($E_e >> E_p$). As particles drift from the decay region, they pass through the region where the magnetic field decreases rapidly from 4 T to 1 T. In the frame of the decay particles, the rate of change of the magnetic field is small compared to their gyration frequency, therefore they transport adiabatically. The decrease of the intensity of the magnetic field implies that the gyration radii of the particles increase, reducing their transverse component of momentum while the longitudinal component is increased (adiabatic invariant; conservation of momentum). This longitudinalization of momentum is particularly important for electrons, since it reduces the number of electrons that are Penning-trapped in the high field region and since they hit the detector more normal to its surface, reduces their probability of being backscattered. Additionally, this configuration of the magnetic fields serves as a magnetic mirror that reflects backscattered electrons. Since decay protons are emitted with very low energies (<750 eV), they need to be accelerated for detection. For that purpose, the spectrometer has tubular high
voltage electrodes kept at 30 kV in the region of the decay volume and 0 V at both ends of the spectrometer (see figure 3), accelerating the decay protons at 30 keV as they approach the lowest magnetic field region. Since the energy of the decay electrons will be reduced by 30 keV in this electric field, there is a lower limit of 30 keV in the energy of the electrons that can be detected with this apparatus. Electrons and protons are detected in the same 2mm thick silicon detectors, which are about 12 cm diameter circles segmented in 127 hexagonal pixels of about 1 cm$^2$ of area.

Figure 2. Symmetric 4$\pi$ neutron decay spectrometer for electron-proton coincidence.

Figure 3. Profiles of electric and magnetic fields along the spectrometer axis.

The design of the spectrometer allows the reduction of backgrounds because the magnetic field lines passing through the decay volume at ultra-high vacuum ensures that the only particles that hit the detectors are those emitted in the decay. Additionally, the spectrometer prevents false coincidences: the decay particles drift along the magnetic field lines with gyration radii that are, in the region of lowest magnetic field, 5mm at most, therefore they are transversally located within two gyration radii (1 cm), a distance which is comparable to the pixel size;
in real coincides, both particles should hit the detector either on the same pixel or in an immediate adjacent pixel (if emitted in the same direction), or in a conjugate pixel in the opposite detector (if emitted in opposite directions). With this apparatus, it will be possible to determine, for each event: the neutron beam polarization, the electron energy, and the direction of the axial component of the electron and proton momenta. This information is used to extract the correlation parameters $a$, $b$, $B$ and $A$. In addition, since decay protons travel first along the magnetic field lines in a region of zero electric field before being accelerated, the time they spend in this region is by far larger than the time they spend in the spectrometer after acceleration. Thus the time difference between the electron and proton arrival provides information of the axial component of the proton momentum, which can be used to obtain information of the kinematics of the decay that improves the sensitivity for the determination of $a$.

3. Advances

3.1. Si detectors

There is a 20% probability for electrons to be backscattered by the detector, and from those 85% will be reflected back by the magnetic mirror and 15% will escape and hit the opposite detector. In order to reconstruct the latter, which represent 3% of the total, it is necessary to have time resolution of the order of the time of flight of electrons between the two detectors (a few ns), so that it is possible to determine which detector was hit first. Additionally, the detectors must ensure that protons will lose a small amount of energy ($\sim 100$ eV) in the surface layer. Both requirements set very stringent conditions for the detectors. Fortunately, each of these requirements has been individually met in prototypes and full detector prototypes are at present under testing [10].

3.2. Precision neutron polarimetry

Parameters $A$ and $B$ are directly related to the neutron polarization. To have a $10^{-4}$ precision in the determination of this parameters, knowledge of the neutron polarization to the $10^{-3}$ level is required. As mentioned before, one possibility is to use a $^{3}$He spin filter to polarize the neutron beam. This is a well established technology that has been extensively used in other experiments, however, the requirements for $abBA$ are beyond the present precision limits of the technique, which are typically of a few percent, and therefore development needs to be done. The functioning of these filters is based on the large dependence that the capture of neutrons on $^{3}$He has with their relative spin direction. Polarized $^{3}$He gas volumes are achieved polarizing the valence electron of a small amount of Rb inside a glass cell (that also contains the $^{3}$He) by optical pumping with circularly polarized laser light. Spin exchange with Rb polarizes the $^{3}$He.

A detailed description of these filters can be found at [6, 7].

The practical difficulties in performing precision neutron polarimetry with this technique can be divided into categories: (i) the physics of the $n$-$^{3}$He reaction; (ii) the intrinsic properties of the beam that prevent a perfect relationship between neutron time-of-flight and energy ( moderation time, $\beta$-delayed neutrons, etc.); (iii) depolarizing interactions with materials and electromagnetic fields that conform the experimental apparatus; (iv) detector backgrounds that affect the neutron transmission measurements from where neutron polarization is determined; and (v) imperfect properties of the $^{3}$He spin filters (variations with position in $^{3}$He thickness and absorption and scattering of neutrons on the cell glass windows). The uncertainties produced by the first three are below the $10^{-4}$ level and therefore do not affect neutron polarization at the precision we are seeking. However, the last two represent the greatest difficulties in using this method for precision neutron polarimetry. Backgrounds come from $\gamma$-rays or neutrons that are not part of the beam but have scattered into the detector. From these, neutrons are the main concern because the detector efficiency ($^{3}$He ionization chamber) for gammas is very low compared to that for neutrons. At the Los Alamos Neutron Science Center (LANSCE) of Los Alamos National Laboratory...
Laboratory (LANL) we performed several neutron polarimetry measurements addressing the main identified source of background (neutrons scattered on spin filter glass cell and other beamline components). The analysis of these measurements has not been finalized yet, however significant improvement in precision is anticipated.

3.3. Prototype adiabatic RF spin flipper

To not lose precision in neutron polarization during the spin reversal, a nearly 100% efficient spin flipper is required. This can be achieved by an adiabatic RF spin flipper, which consists of an RF field in the beam propagation direction (z-axis) with a sine modulated amplitude

$$\vec{B}_{RF}(z, t) = A \sin \left( \frac{\pi (z + L/2)}{L} \right) \sin(\omega_{RF} t) \hat{k},$$

and a static field along the vertical direction (x-axis) with a cosine modulated amplitude

$$\vec{B}_s = \left[ B_o + A \cos \left( \frac{\pi (z + L/2)}{L} \right) \right] \hat{i}.$$ (6)

The spin flipper along the z-axis occupies the region from $-L/2$ to $L/2$ (total length $L$) and $B_o$ is the amplitude of the vertical static magnetic field used for conserving the neutron beam polarization during transport. Before entering the SF region, the neutron spins precess about this field with Larmor angular frequency given by $\omega_o = \gamma B_o$, where $\gamma$ is the neutron gyromagnetic ratio. If $\omega_{RF}$ matches $\omega_o$, then, in the frame of reference of the neutron spin (a frame rotating about the x-axis with angular frequency $\omega_o$), the effective field produced by the sum of RF and static magnetic fields is constant in amplitude ($A$) and with direction that changes from being parallel to $\vec{B}_o$ at the beginning of the SF to anti-parallel at the end:

$$\vec{B}_{eff} = \left[ A \cos \left( \frac{\pi (z + L/2)}{L} \right), -A \sin \left( \frac{\pi (z + L/2)}{L} \right), 0 \right].$$ (7)

For neutron spins to continue precessing about the effective field and thus rotate, it is essential that the change of direction of this field is adiabatic; this means that the rate of change of the effective field needs to be small compared to the precession angular frequency of the neutrons about it ($\omega_{eff} = \gamma |\vec{B}_{eff}| = \gamma A$)

$$\frac{\pi}{L/\nu} \ll \gamma A.$$ (8)

The above condition sets the upper limit in the energy of the neutrons whose spin can be efficiently rotated by 180°. This limit depends on the length ($L$) and amplitude of the SF fields ($A$). A first prototype was designed and constructed at the Physics Institute of the National Autonomous University of Mexico (UNAM). The device is shown in figure 4. It consists of a set of four squared coils to produce the static cosine-modulated magnetic field and a solenoid for the horizontal sine-modulated RF field. For the squared coils, if neutron beam propagates from left to right, up and down left coils have the same current and opposite to that of up and down right coils. The solenoid is inside an aluminum can that prevents the RF power to leak out the SF region. The thickness of the can walls is 5 mm, except for the windows on the path of the neutron beam, which are 0.5 mm thick to minimize the neutron absorption/scattering, and yet being thick enough to provide shielding for 29 kHz RF (the Larmor frequency $f_o = \omega_o/2\pi$ for the field $|B_o| = 10$ G). In figure 5, the calculated and measured magnetic fields along the SF axis are shown. The total length of the SF is 40 cm and the amplitude of modulation of the component fields is 4 G. With these parameters we get the adiabaticity condition $E_n << 456$ meV, and the energy of the neutrons used in the experiment is, at most, a few meV. The first prototype testing was performed at LANSCE. Figure 6 shows a frequency distribution of
the average neutron transmission through a $^3$He polarization analyzer located after the SF; two distributions, corresponding to the two spin states can be observed. The efficiency of this prototype has not been measured yet.

![Image of the first prototype of the adiabatic RF SF tested at LANSCE.](image)

**Figure 4.** The first prototype of the adiabatic RF SF tested at LANSCE.

![Graph showing measured and calculated magnetic field amplitudes along the SF axis.](image)

**Figure 5.** Measured and calculated magnetic field amplitudes along the SF axis.
Figure 6. Frequency distribution of the average neutron transmission through a $^3$He analyzer cell. Two distributions corresponding to the two spin states (SF on and off) can be identified.

4. Conclusions
The abBA experiment will be performed within the next few years at the fundamental neutron physics beamline (FnPB) of the ORNL-SNS. Research and development in different aspects of the experiment like neutron beam polarization precision, charged particle detectors with very good time resolution and thin dead-layer, and a highly efficient adiabatic RF spin flipper are currently undergoing. A good degree of advance has been achieved for all of them. Neutron polarization determination to a precision close to $10^{-3}$, with $^3$He spin filters, is expected from the latest measurements at LANSCE. Test measurements with the final version of the charged particle detectors are expected to be performed in the near future. Finally further characterization of the first prototype of the adiabatic RF spin flipper is needed.

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