Neutron Beta Decay Studies with Nab

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Abstract. Precision measurements in neutron beta decay serve to determine the coupling constants of beta decay and allow for several stringent tests of the standard model. This paper discusses the design and the expected performance of the Nab spectrometer.

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A program of precision studies of neutron beta decay is planned with the Nab spectrometer. Nab will use the state of the art neutron beamline (FNPB) at the new Spallation Neutron Source (SNS) in Oak Ridge, TN. The expected results will play a critical role in resolving longstanding discrepancies in the neutron decay world data set, and will allow an extraction of $V_{ud}$, the upper left element of the Cabbibo-Kobayashi-Maskawa matrix. The redundancy inherent in the standard model description of the neutron beta decay process allows uniquely sensitive checks of the model’s validity and limits [1, 2, 3, 4], with strong implications in astrophysics [5].

The aim of the Nab collaboration is to determine $a$, the neutrino electron correlation coefficient, and $b$, the Fierz parameter, in the decay of the free neutron [6]. The $a$ coefficient can be obtained through a measurement of the electron energy $E_e$, and the momentum $p_p$ of the corresponding proton. In zeroth order approximation, the $a$
coefficient is given by the slope of the top of the squared proton momentum distribution \( P_p(p^2_p) \) for a fixed electron energy \( E_e \):

\[
P_p(p^2_p) \propto \begin{cases} 
1 + a \frac{E_e}{p^2_{e}} \frac{p^2_{p} - p^2_{e} - p^2_{\nu}}{2p_{e}p_{\nu}} & \text{if } -1 \leq \frac{p^2_{p} - p^2_{e} - p^2_{\nu}}{2p_{e}p_{\nu}} \leq 1 \\
0 & \text{otherwise}
\end{cases}
\] (1)

In this approximation, electron \( p_e \) and neutrino \( p_\nu \) momenta are functions of the electron energy \( E_e \). The positions of the edges of these distributions \( P_p(p^2_p) \) are sharply defined by the three-body decay kinematics. The Fierz term \( b \) could in principle be determined from a precise measurement of the beta energy spectrum alone. However, the Nab collaboration believes that coincident detection of the accompanying proton is essential in suppressing background. The basic principles of the Nab spectrometer have been described in Refs. [7, 9, 8]. This paper reports on a conceptual design update.

A sketch of the Nab spectrometer is shown in Fig. 1. The Si detectors measure the electron energy with keV-level resolution. Electron energy losses through backscattering are avoided thanks to the magnetic guide field that connects the two detectors at both sides of the decay volume. Electrons might bounce, but are eventually fully absorbed. Their full energy will be determined after adding signals from both detectors. Corrections for dead-layer(s) and bremsstrahlung will be made. The proton is detected only if it arrives at the upper detector, after a long TOF path and subsequent acceleration. Its momentum \( p_p \) is inferred from the proton’s time of flight \( t_p \) relative to the electron hit. Once the proton momentum is longitudinalized by the magnetic field, \( p_p \propto 1/t_p \), but a certain path length is required for that.

Also shown in Fig. 1 is the simulated performance of a realistic electromagnetic design of the spectrometer, and compared to an ideal detector response with \( p^2_p \propto 1/t^2_p \).
Electric field effects are neglected. The edges of the simulated $1/t^2_p$ distribution reflect the detector response function. In comparison to the previous, symmetric design (see Fig. 3 in [8]), the relative width of the response function is considerably smaller in the asymmetric configuration, while maintaining a workable count rate. The bigger flight path length and the sharper magnetic field pinch outweigh the fact that the protons have to pass through the full field pinch.

The Si detector was initially designed by the abBA collaboration [10], and is being refined by the Nab and UCNB collaborations. For first performance studies, see [11].

**TABLE 1.** Predicted uncertainties in $a$ due to imperfect knowledge of spectrometer properties.

| Experimental parameter                                      | Systematic uncertainty $\Delta a/a$ |
|-------------------------------------------------------------|-------------------------------------|
| Magnetic field curvature at pinch                           | $5 \times 10^{-4}$                  |
| ... ratio $r_B = B_{TOF}/B_0$                               | $2.5 \times 10^{-4}$                |
| ... ratio $r_{B, DV} = B_{DV}/B_0$                          | $3 \times 10^{-4}$                  |
| Electrical potential inhomogeneity in decay volume / filter region | $5 \times 10^{-4}$                  |
| ... in TOF region                                           | $1 \times 10^{-4}$                  |
| Neutron Beam position                                       | $4 \times 10^{-4}$                  |
| ... profile (including edge effect)                         | $2.5 \times 10^{-4}$                |
| Adiabaticity of proton motion                               | $1 \times 10^{-4}$                  |
| Detector: Electron energy resolution                        | $5 \times 10^{-4}$                  |
| ... Proton trigger efficiency                               | $2.5 \times 10^{-4}$                |
| Sum                                                         | $1 \times 10^{-3}$                  |

Counting statistics will not be limiting: After about six weeks of data taking, the statistical uncertainty in the determination of $a$ is below 0.1%. Tab. 1 shows the predicted systematic uncertainties. Several additional items (length of TOF region, electron energy calibration, residual gas, background, accidental coincidences, unwanted neutron beam polarization and Doppler effect) have been found to be small if the relevant specifications are met. See [12] for a detailed discussion.

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