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Neutron decay correlations in the Nab experiment

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Abstract.

The Nab experiment will measure the correlation a between the momenta of the beta particle and antineutrino in neutron decay as well as the Fierz term b which distorts the beta spectrum.

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The a correlation can be used to extract the quark mixing matrix element V_{ud} , which is used to precisely test our understanding of the electroweak interaction. A non-zero Fierz term would signal the presence of scalar and tensor currents which must come from new physics beyond the Standard Model of Particle Physics. Nab uses an asymmetric spectrometer to determine the proton time-of-flight and the beta energy in order to reconstruct the angular correlation between the electron and antineutrino. The charged particles are detected using thick, large-area, segmented silicon detectors, which must be held at a potential of -30 kV to detect the very low energy protons. A 24 channel prototype system has been tested and found to meet specifications of 3 keV full-width half maximum (FWHM) energy resolution at 30 keV, 50 ns signal rise times, and thresholds < 10 keV. The 128 ch fully instrumented detection system is currently in development. Silicon drift detectors in development by the TRISTAN collaboration can reach an energy resolution as low as 135 eV FWHM at 6 keV, and could enable the next generation of neutron beta decay experiments.

1. Introduction

Precision measurements in neutron decay are used to test the weak interaction in the Standard Model of Particle Physics, and provide important inputs for astrophysical processes such as solar fusion cross sections [1] and big-bang nucleosynthesis calculations [2]. One of the most precise tests of the weak interaction is performed by testing the requirement that the Cabibbo Kobayashi Maskawa (CKM) matrix that describes the mixing of quarks in the weak interaction must be unitary. The uncertainty of the most demanding check of unitarity, $V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1$, is dominated by the matrix element $V_{ud} = 0.97417(21)$, currently determined most precisely from the lifetimes of the set of superallowed Fermi $0^+ \rightarrow 0^+$ decays [3]. Recently, updated lattice QCD simulations have introduced some tension into the values of V_{us} determined from kaon decays and therefore CKM unitarity [4]. This situation highlights the importance of having multiple independent systems as a check against unidentified experimental errors, or for possible new physics.

V_{ud} is also determined from several other systems but with much larger uncertainty: the $T = \frac{1}{2}$ mirror nuclear decays ($V_{ud} = 0.9719(17)$) [5], pion decay ($V_{ud} = 0.9728(30)$ [6], and neutron decay ($V_{ud} = 0.9758(16)$) [7]. Neutron decay is not sensitive to some of the nucleus-dependent theoretical corrections that are included in the superallowed Fermi and mirror nuclear decays, and with improved experimental uncertainties should allow for a more precise determination of V_{ud} . Because the neutron is a mixed Fermi and Gamow-Teller decay, two observables are required to fix the ratio of axial-vector to vector form factors λ , which must be experimentally determined, and extract V_{ud} .

To be competitive with superallowed $0^+ \rightarrow 0^+$ Fermi decays, the uncertainty in the neutron lifetime must be improved to ~ 0.3 s and the uncertainty in λ to roughly the 10^{-4} level. The Particle Data Group (PDG) recommendation for the neutron lifetime is 880.3(1.1) [7], however there is a $\sim 3 \sigma$ discrepancy between experiments performed with cold neutrons [8, 9] and ultracold neutrons [10–14]. The parameter λ is known primarily from the angular correlation between the neutron spin and the emitted beta particle (the β -asymmetry A) from $A = \frac{-2|\lambda|(|\lambda|+1)}{1+3\lambda^2}$ in the Standard Model prediction. The most recent and precise measurements of the β -asymmetry are from the UCNA and Perkeo II experiments, which found $\lambda = -1.2755(30)$ [15] and $-1.2748(14)$ [16], respectively, and are somewhat in tension with previous measurements.

The correlation between the electron and antineutrino momenta, a , can be used to extract λ with nearly the same precision as A , from $a = \frac{1-\lambda^2}{1+3\lambda^2}$. The value of this correlation recommended by the PDG is $a = -0.103(4)$. The most precise determinations of a to date have used the technique of measuring the proton energy spectrum distortion [17, 18]. The slight negative value of a results in a slight preference for electrons and antineutrinos to be anti-aligned, and therefore

an excess of protons with lower energies compared to higher energies, which is apparent in a measurement of the shape of the proton energy spectrum.

Two ongoing experimental efforts, aSPECT [19] and aCORN [20], are attempting to improve the precision in a by taking the approach of measuring the proton energy spectrum and determining the momenta of the proton and electron, respectively. The aSPECT experiment uses a retardation spectrometer to determine the integral of the proton energy spectrum, with a variable retardation voltage between the cold neutron beam and a silicon drift detector so that only protons with sufficient kinetic energy can pass to be detected. aSPECT is currently analyzing data from its 2013 run with an expected precision of $\delta a/a \sim 1\%$ [21], and an ultimate reach of $\delta a/a \sim 0.3\%$ is achievable.

The aCORN experiment instead determines a by comparing the ratio of counts with proton times-of-flight corresponding to aligned and anti-aligned electrons and antineutrinos. The aCORN spectrometer only accepts electrons and protons with momenta nearly parallel to the spectrometer axis, and electrons emitted in one direction. Therefore, the antineutrino momentum is nearly parallel with the electron momentum and has equal probability to be aligned or anti-aligned for accepted events, except for the influence of the parameter a . aCORN performed a data-taking run at the National Institutes of Standards and Technology NG-6 beamline from 2013-2014 and is currently analyzing the data. They expect to reach an uncertainty of a few percent. aCORN recently completed a second run with an improved apparatus on the high flux NG-C beamline in 2016 with a goal uncertainty of $\delta a/a \sim 1\%$.

2. Nab Experiment Overview

The aSPECT approach of measuring an asymmetry in proton time-of-flight allows for a more sensitive determination of a than by performing proton spectroscopy, but suffers from reduced statistics available due to the limited acceptance of the spectrometer. The Nab collaboration has proposed a different approach [22, 23] that also uses the proton time-of-flight to determine a , but with full kinematic acceptance of the electrons. The Nab experiment is the next major experiment to use the Fundamental Neutron Physics Beamline at the Spallation Neutron Source at Oak Ridge National Laboratory [24]. It is currently being installed and is expected to begin commissioning in early 2018. Nab is designed to achieve a precision in a of $\delta a/a \sim 10^{-3}$ as well as place a limit on a possible Fierz interference term which distorts the beta energy spectrum of $\delta b \sim 10^{-3}$. The Fierz interference term has never been measured in neutron decay and is predicted to be zero in the Standard Model. A non-zero Fierz term would indicate the presence of Scalar or Tensor currents which must originate from Beyond Standard Model physics [25, 26]. Currently, very tight constraints on Scalar currents comes from the set of superallowed $0^+ \rightarrow 0^+$ decays [3], and Tensor currents are best constrained from pion decay [27, 28], or neutron and nuclear decay [29, 30].

We can understand how to extract the parameter a from the measurable quantities in Nab by considering conservation of momentum,

$$p_p^2 = p_e^2 + 2p_e p_\nu \cos\theta_{e\nu} + p_\nu^2, \quad (1)$$

where the valid values of proton momentum p_p are given by the requirement that the cosine of the angle $\theta_{e\nu}$ between the electron and antineutrino momenta p_e and p_ν , respectively, be between ± 1 . In the infinite nuclear mass approximation, both p_e and p_ν are a function of only E_e . The kinematically allowed values for the squared proton momentum as a function of E_e and $\cos\theta_{e\nu}$ form a tear-drop shape (Fig. 1). At fixed E_e (assuming zero neutrino mass) the neutron decay rate W is proportional to

$$W \propto 1 + a \frac{p_e \cos\theta_{e\nu}}{E_e} \quad (2)$$

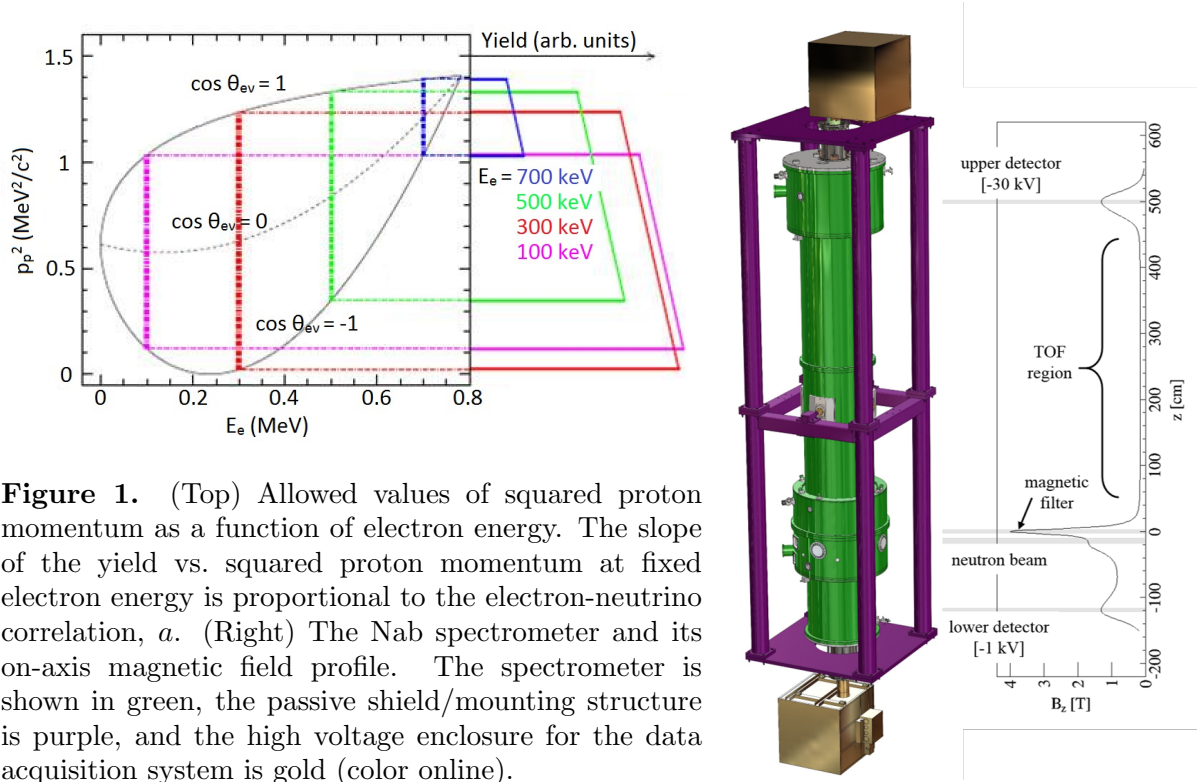


Figure 1. (Top) Allowed values of squared proton momentum as a function of electron energy. The slope of the yield vs. squared proton momentum at fixed electron energy is proportional to the electron-neutrino correlation, a . (Right) The Nab spectrometer and its on-axis magnetic field profile. The spectrometer is shown in green, the passive shield/mounting structure is purple, and the high voltage enclosure for the data acquisition system is gold (color online).

where $\cos \theta_{e\nu}$ depends linearly on p_p^2 . Therefore, the slope of W vs. p_p^2 at fixed E_e is proportional to the parameter of interest, a .

The energy of the proton is quite small, with an endpoint of 751 eV, making the direct determination of the proton momentum quite challenging. In the magnetic spectrometer, the charged particles that result from the decay spiral along magnetic field lines and are guided to a detector, so that the time-of-flight depends more strongly on emission angle with respect to the spectrometer axis than on momentum. The strategy in Nab is to select only protons emitted in a narrow cone along the spectrometer axis, and then use a large field expansion to further parallelize the momentum. The Nab spectrometer and magnetic field profile are depicted in Fig. 1. The spectrometer is asymmetric, with a longer arm used for the proton time-of-flight measurement. Just above the neutron beam guide, which resides in a field of about 1.7 T, the magnetic field increases sharply to 4 T. This magnetic field “pinch” reflects protons that are not nearly parallel with the field lines. To longitudinalize the particles’ momenta, the field then drops to 0.2 T for the length of the time-of-flight region. The detectors are positioned at about 1.3 T. Construction of the magnet is nearly complete, with an expected delivery during the summer of 2017.

Because of their low energy, protons require an accelerating potential to be detected. To measure the a correlation, only the upper detector has the accelerating potential applied to detect protons, whereas electrons are measured in either detector. A small accelerating potential is applied to the lower detector which is insufficient to allow proton detection but prevents the protons from being reflected back to the upper detector and skewing the time-of-flight measurement. To measure the b correlation, the -30 kV accelerating potential is applied to the lower detector where there is no field pinch, to increase the counting rate.

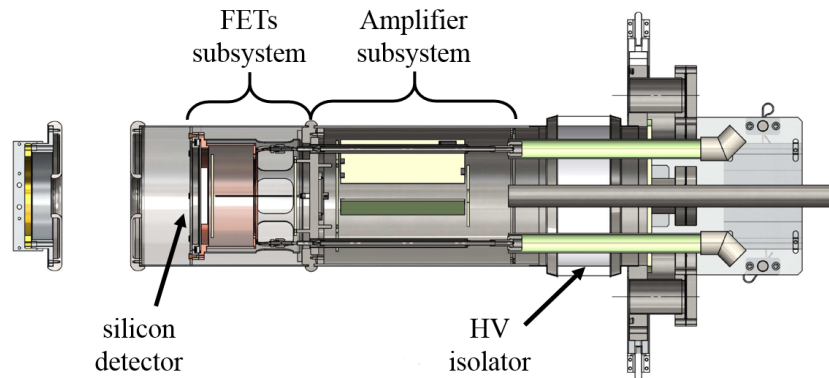


Figure 2. Prototype detector mounting assembly (color online).

3. Prototype Detection System

The detectors developed for Nab are unique in that they were designed to enable direct detection of both the recoil proton and electron with excellent energy and timing resolution and good position sensitivity. They are 1.5–2 mm thick, with $\sim 100 \text{ cm}^2$ active area silicon detectors, segmented into 127 hexagonal pixels. The detectors were developed in collaboration with Micron Semiconductor, Ltd. [31] and the UCNB collaboration [32,33]. The detectors exceed the requirements of the Nab experiment, with a 100 nm entrance window (dead layer) and 3 keV energy resolution measured using a proton beam at the Triangle Universities Nuclear Laboratory [34]. Protons with energies as low as 15 keV were detected. In Nab, a -30 kV accelerating potential will be used for proton detection.

A prototype detection system has been developed to characterize the expected performance (Fig. 2). The prototype includes 19 instrumented single pixels plus 18 pixels ganged into 4 channels of 4 or 5 pixels. The preamplifier consists of two subsystems, with the first containing 3 boards of 8 channels with the FETs and feedback loop, mounted at the detector in vacuum and cooled by connection to liquid nitrogen lines, and the second containing 4 boards of 6 channels with later gain stages, mounted in air at room temperature. The data acquisition system is based on the National Instruments PXIe-5171R digitizers [35]. The mounting structure was designed to mount into the UCNA spectrometer [36] and position the detectors in the field expansion region, at 0.6 T. The design requirements for the UCNA spectrometer are similar to that of Nab, in particular, the diameter is the same. The mount includes a 30 kV ceramic high voltage isolator, which allows a -30 kV accelerating potential to be applied to the detector, electronics, and data acquisition system.

The performance of the prototype detection system has been demonstrated to meet specifications for Nab [37]. The preamplifier signals have rise times of $\sim 50 \text{ ns}$, which translates to a time resolution of several ns, depending on signal amplitude. The energy resolution was determined to be $\sim 3 \text{ keV}$ at 30 keV using X-ray sources, with an energy threshold $< 10 \text{ keV}$. The leakage current per pixel was $\sim 1 \text{ pA}$ at the operating detector temperature of 175 K. The preamplifier electronics were found to exhibit no nonlinearities above 0.3%, the limit of the input pulser used for characterization.

Electron-proton coincidences from neutron beta decay were measured using this system. The measurement was performed using ultracold neutrons from the LANSCE source [38]. To increase the same-side coincidence rate the neutrons were polarized by a 6 T magnet followed by an adiabatic fast passage spin flipper [39]. Coincident protons are identified by their energy deposition in the active part of the Si detector of slightly less than 20 keV, and by their delayed

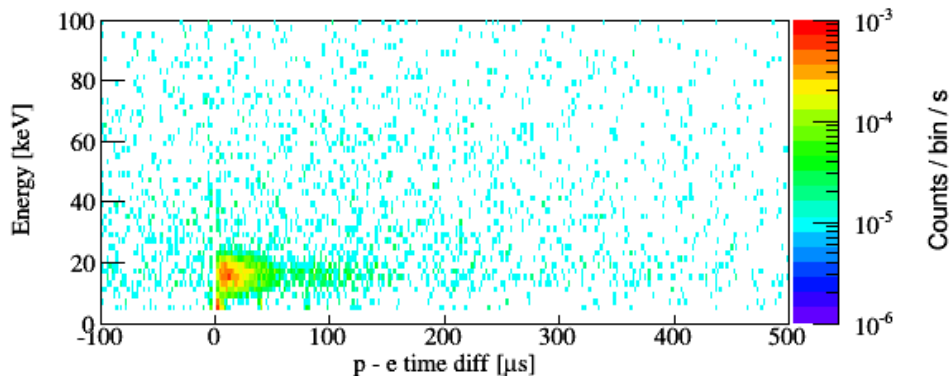


Figure 3. Protons deposit < 20 keV in the detector after the dead layer and arrive tens of μs after an initial electron event (color online).

detection time relative to the electron (Fig. 3). This system has also been used to demonstrate an important systematic consideration for experiments which use finite detectors in magnetic spectrometers, in a recent study of the non-monotonic point-spread function of monoenergetic particles in a homogeneous magnetic field [40].

4. Fully Instrumented Detection System

The design of the fully instrumented detection system includes several considerations to improve reliability and performance over the prototype. One major change is the interface to the detector. The prototype detectors included surface mounted pin header sockets for connection to the preamplifier assembly and bias input, which were easily damaged after many reconnections. The strategy chosen for the fully instrumented system was inspired by the KATRIN detection system [41], and instead uses spring-loaded pogo pins to make electrical contact. The concept was tested using a 4 channel prototype in which the preamplifier assembly directly contacted the gold contact of a 1 in. quadrant detector developed by Micron Semiconductor Ltd. The prototype was physically robust to dozens of reconnection and cryogenic cycles.

An alternate contact configuration was chosen for the detectors to further improve confidence that the detectors could not be damaged, and to meet other requirements of the detection system. In the chosen design, the pogo-pins contact pads on the ceramic mount of the detector, which are wire-bonded to the pixels (Fig. 4). All silicon pixels and partial pixels are accessible through the array of holes in the ceramic. The interface board is a Rogers 4003C ceramic composite [42], which includes the pogo-pins to contact the detector as well as contact pads on the back-side to interface to the preamplifier electronics, also through pogo-pins. This interface will serve as a vacuum feedthrough, such that the electronics can be disconnected without breaking vacuum or warming up the cold-bore spectrometer, avoiding several weeks of delay if an electronics channel should fail. A prototype interface board with through-hole pogo-pins and an indium vacuum seal was found to have a helium leak rate below 10^{-9} mbar-l/s at cryogenic temperature. The detectors are currently being assembled by Micron Semiconductor Ltd.

The fully instrumented system multiplies the number of channels by more than five, but the channel density of the boards is the same as in the prototype. This design implements the 16 FET boards and 22 amplifier boards radially about the spectrometer axis (Fig. 4). The FET assembly is mounted directly behind the detector and contacts the detector interface by pogo-pin contacts. It is mounted inside a copper cold can and resides in a separate vacuum from the detector and spectrometer. The FET assembly and amplifier assembly is separated by another

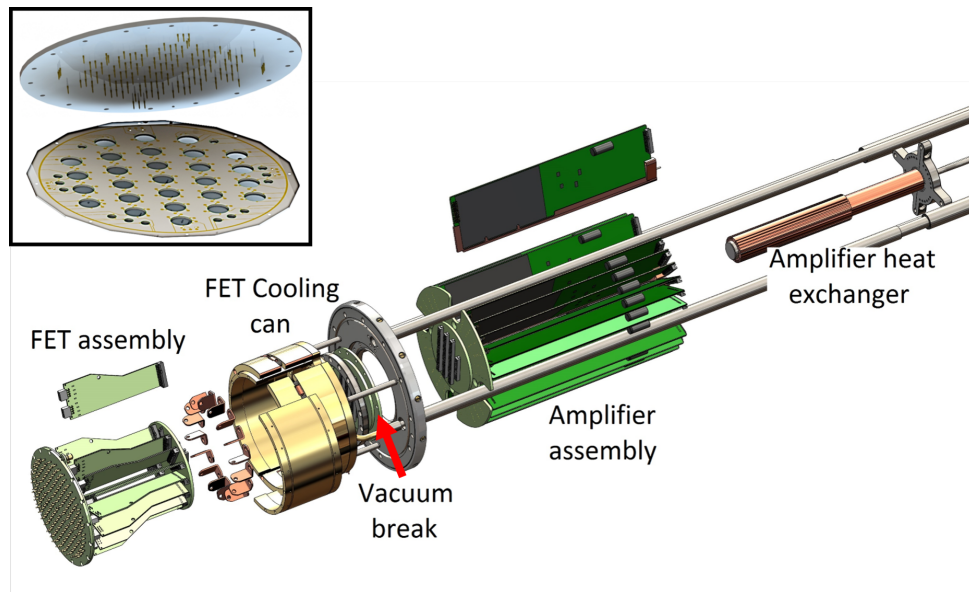


Figure 4. Exploded diagram of the 128 channel, fully instrumented preamplifier electronics. (Inset) Redesigned detector interface, including pogo-pin contacts (color online).

Rogers 4003C interface board which serves as a high channel density vacuum feedthrough. The amplifier assembly is mounted around a central axis which provides water cooling for the boards to maintain this section at room temperature.

The redesigned mounting structure includes an improved electrode design for better electric field uniformity and reduced Penning traps, especially near the ceramic high voltage break, which could lead to high voltage breakdown (Fig. 5). It is re-entrant into the Nab spectrometer to position the detectors at the 1.3 T region. The design allows for the preamplifier assembly to be extracted without venting the spectrometer, and for the amplifier assembly to be extracted separately. Provision for a load lock assembly is included, if a need to change detectors frequently is identified. In the prototype system, liquid nitrogen was used to cool the detector and FET assembly; however this was associated with added microphonics noise in the detector signals.

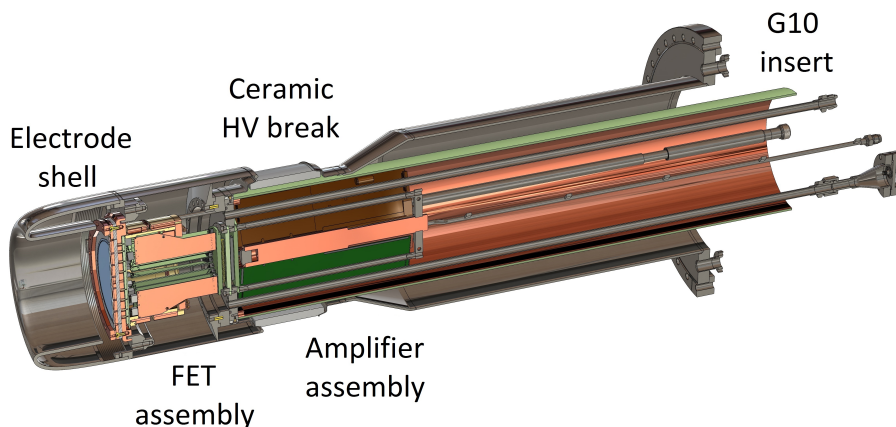


Figure 5. Diagram of mount with detector and electronics installed (color online).

The detector and FET assembly will instead be cooled by circulating cold helium gas in the cooling lines. As the FET assembly is in its own vacuum system, an exchange gas can be used to more rapidly cool the assembly. A copper-coated G10 insert isolates the amplifier assembly and cooling/vacuum lines from the mounting structure held at ground potential. The mounting assembly is currently in fabrication.

5. Detectors for Future Neutron Decay Experiments

The detectors developed for Nab represent a significant advance for measurements of neutron beta decay observables. To achieve even higher sensitivities in next generation experiments, for example ABba [43], further improvements in detector technology may be required. The TRISTAN project is developing detectors which may be of interest for future neutron beta decay experiments. TRISTAN will use the KATRIN spectrometer [44] to search for a signature of a keV-scale sterile neutrino in the beta spectrum of tritium decay, which appears as a “kink” in the shape of the spectrum [45]. The TRISTAN experiment will improve upon the silicon detectors currently used by KATRIN [41] by implementing silicon drift detectors in a hexagonal pixel array. The “point-contact” anodes reduce the capacitance and therefore noise of the pixel, even for large pixel area. An energy resolution as low as 135 eV (150 eV) FWHM at 6 keV has been achieved with prototype detectors with (and without) detector cooling and using a Cube CMOS preamplifier developed by XGLab [46] (Fig. 6).

A drawback of the silicon drift detector is the increased time for the electron-hole pairs to be collected. The drift paths of charges in various detector geometries were simulated using a modified version of the SIGGEN code [47] (Fig. 6). To achieve similar rise times as the Nab experiment (< 50 ns), pixel diameters could be reduced to ~ 1 mm. To avoid substantially increasing the number of channels that must be instrumented, several pixel outputs could potentially be combined into a single electronics channel. The point-contact anodes are most relevant for applications that do not require fast timing, such as for detection of only protons. The silicon drift detector used by aSPECT has 1 cm^2 pads and has drift times of order μs . It has a 30 nm aluminum layer covering the silicon entrance window, which has a charge collection efficiency that slowly varies from 0% to 100%.

A detector with a very thin dead layer in a form factor similar to the Nab detectors would significantly reduce systematic uncertainties related to detection of the proton and electron. The dead layer introduces an uncertainty in the energy reconstruction of the electron energy and in identifying backscattered electrons which deposit only a portion of their energy in the detector and traverse the dead layer twice. The dead layer is also an important limitation in the detector’s ability to detect protons. Fig. 6 depicts the required accelerating voltage to produce a detectable proton for several values of dead layer thickness and deposited energy (above the noise), as predicted by the SRIM code [48]. A dead layer as thin as 30 nm or even 10 nm of silicon may be achievable for a thick and large area similar to the dimensions required for Nab. Reducing the required accelerating potential would dramatically simplify the design constraints of the detection system mount in future experiments.

6. Summary

The novel approach used by the upcoming Nab experiment will enable a precision measurement of the electron neutrino correlation at the level of $\delta a/a \sim 10^{-3}$ and the first direct measurement of the Fierz interference term at the level of $\delta b \sim \text{few } 10^{-3}$ in neutron decay. A prototype detection system has been used to detect the proton and electron in coincidence from neutron beta decay with rise times of 50 ns, energy resolution of 3 keV, and thresholds < 10 keV. The fully instrumented, 128 ch detection system is in fabrication. The Nab experiment is currently being installed at the Fundamental Neutron Physics Beamline at the Spallation Neutron Source

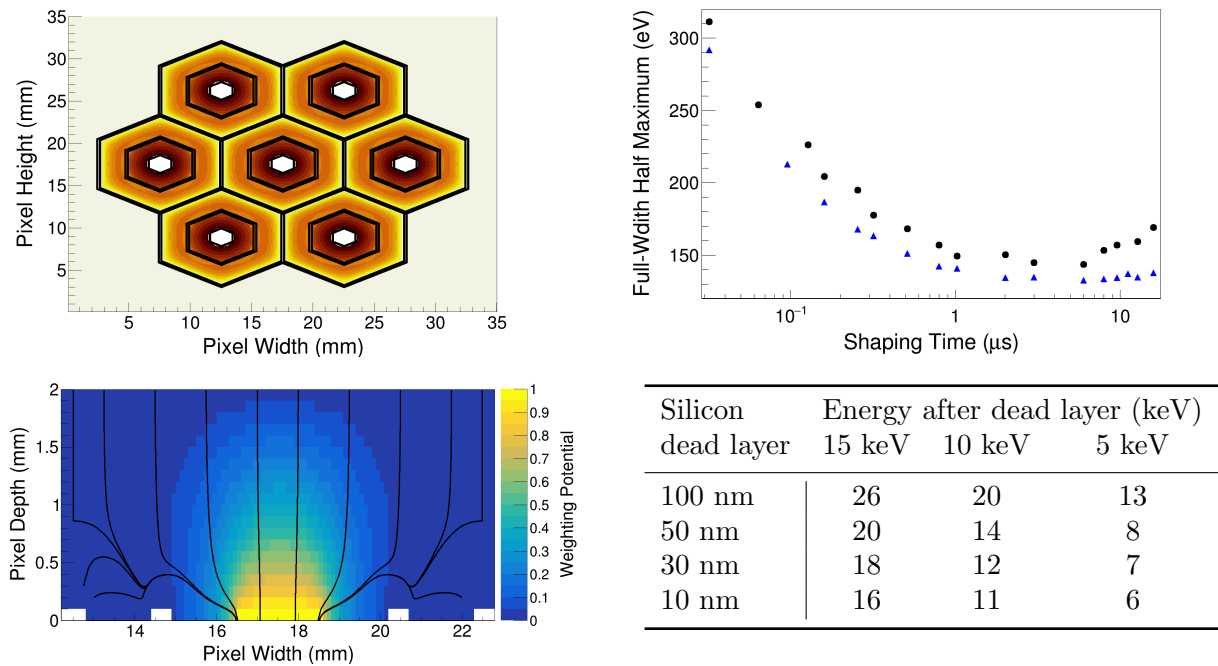


Figure 6. (Top left) Schematic of hexagonal silicon drift detector with dimensions similar to the Nab detector. The steering rings (black) surrounding each anode (white) speed up charge collection time and prevent areas of incomplete charge collection. (Top right) Full-width half maximum of ~ 6 keV X-rays from ^{55}Fe vs. shaping time for detector uncooled (black circle) and cooled to -30°C (blue triangle). (Bottom left) Weighting potential of central pixel and simulated drift paths of charges in a detector with dimensions similar to the Nab detector. Steering electrodes are indicated by white and the anode by yellow. (Bottom right) Required accelerating potential for protons to deposit the indicated energy in the active area of the detector for various values of a silicon dead layer. (color online)

with expected commissioning in 2018. Future detector designs with thinner dead layer and point contact geometry appear promising and may be interesting for future neutron decay experiments.

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