Project Update and Beamtime Request

The Nab (Neutron ‘a’ and ‘b’) Experiment

H. Acharya,[a] R. Alarcon,[b] S. Baeßler,[c,d] L. Barrón Palos,[e] D. Bowman,[d] L. Broussard,[d] A. Bryant,[c] J. H. Choi,[f] L. Christie,[h] T. Colaizzi,[c] V. Cianciolo,[d] S. Clymer,[b] C. Crawford,[a] G. Dodson,[g] N. Fomin,[h] A. Hagemeier,[c] J. Fry,[i] M. Gericke,[n] R. Godri,[h] F. Gonzalez,[d] J. Hamblen,[j] L. Hayen,[k] A. Jezghani,[l] C. Landgraf,[c] N. Macsai,[n] M. Makela,[m] J. Mammei,[n] R. Mammei,[o] D. Mathews,[d] B. Plaster,[a] A. Mendelsohn,[n] P. Mueller,[d] A. Nelsen,[a] H. Rahangdale,[h] J. Ramsey,[d] J. Pate,[h] S. Penttila,[d] D. Počanić,[c] A. Saunders,[d] W. Schreyer,[d] E. M. Scott,[p] A. Shelby,[f] R. J. Taylor,[f] A. Tewsley-Booth,[a] I. Wallace,[h] A. R. Young.[f]

(Current active members of the Nab Collaboration)

[a] Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506, USA
[b] Department of Physics, Arizona State University, Tempe, AZ 85287–1504, USA
[c] Department of Physics, University of Virginia, Charlottesville, VA 22904–4714, USA
[d] Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
[e] Universidad Nacional Autónoma de México, Mexico City, D.F., Mexico
[f] Department of Physics, North Carolina State University, Raleigh, NC 27695-8202, USA
[g] Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[h] Department of Physics and Astronomy, University of Tennessee, Knoxville, TN 37996, USA
[i] Department of Physics, Geosciences, and Astronomy, Eastern Kentucky University, Richmond, KY 40475, USA
[j] Department of Chemistry and Physics, MC 2252, Univ. of Tennessee-Chattanooga, Chattanooga, TN 37403, USA
[k] Laboratoire de Physique Corpusculaire, Caen, France
[l] Partnership for an Advanced Computing Environment, Georgia Institute of Technology, Atlanta, GA 30332, USA
[m] Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[n] Department of Physics, University of Manitoba, Winnipeg, Manitoba, R3T 2N2, Canada
[o] Department of Physics, University of Winnipeg, Winnipeg, Manitoba R3B2E9, Canada
[p] Department of Physics, Centre College, 600 West Walnut Street, Danville, KY 40422 USA

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Executive Summary: The Nab experiment, currently commissioning on Beamline 13 at the Spallation Neutron Source (SNS), is designed to improve precision of the extraction of the quark mixing matrix element V_{ud}, shed light on experimental tensions within the neutron beta decay dataset, and search for evidence of Scalar and Tensor currents not predicted in the Standard Model. After overcoming experimental challenges requiring a repair to the spectrometer and an upgrade to the detection system electronics, the Nab collaboration aims to transition from commissioning to first fully instrumented physics data-taking within the next SNS accelerator cycle, ending November 2024. To meet its precision goals, the Nab experiment anticipates requiring data-taking for two calendar years, 2025-2026, and requests an additional year of contingency to accommodate the remaining unresolved risks.

1. Scientific motivation and experimental landscape

The Standard Model description of the mixing of quarks in the weak interaction must obey a simple yet powerful principle—it must be unitary. The mixing of quarks is represented by the Cabibbo-Kobayashi-Maskawa (CKM) matrix, and the most precise test of its unitarity relies on the first two elements: V_{ud}, which describes up-down transitions in nuclear systems, and V_{us}, primarily determined from kaon decays. Following updates to the inner radiative correction impacting

V_{ud} [1], a significant discrepancy with unitarity was revealed, which now stands in tension by a few standard deviations [2]. Significant internal inconsistencies are observed within the systems used to determine V_{ud} and V_{us} and must be resolved before the unitarity test can be applied with confidence. Addressing the apparent non-unitarity of the quark-mixing matrix was emphasized as one of the highest priorities for the Fundamental Symmetries, Neutrons, and Neutrino community [3] and is prominently featured in the 2023 Nuclear Physics Long Range Plan [4].

V_{ud} is determined most precisely using the set of Superallowed Fermi nuclear decays, where the value recommended by the Particle Data Group (PDG), $V_{\mathrm{ud}} = 0.97367(11)_{\mathrm{exp.}}(13)_{\Delta_R^V}(27)_{\mathrm{NS}}$ [2], is dominated by uncertainty in the nuclear structure corrections, which may be challenging to resolve [5]. This dataset also places strong limits on possible Scalar couplings not present in the Standard Model. Other systems which can make competitive determinations include the nuclear mirrors, the neutron, and the pion. Nuclear mirror decays are more complex than the Superallowed Fermi decays and understanding of those nucleus-dependent corrections lags behind [5], while pion decay remains limited by experimental uncertainties, in particular due to the tiny branching ratio [6]. The neutron system offers a compelling opportunity to inform the situation in the near term, if experimental inconsistencies within the dataset can be resolved. Currently the PDG recommends an average which inflates the errors to account for the disagreement, $V_{\mathrm{ud}} = 0.97441(28)_{\tau_n}(82)_{\lambda}(13)_{\Delta_R^V}$ [2].

As a mixed system the neutron requires two inputs to determine V_{ud}, the lifetime plus the ratio $\lambda = g_{\mathrm{A}}/g_{\mathrm{V}}$ of axial-vector and vector couplings, which can be determined from correlations among the decay particles. The neutron is also sensitive to non-Standard Model Scalar and Tensor currents which induce a distortion to the beta spectrum characterized by a nonzero Fierz term b. The long-standing discrepancy between different techniques for measuring the neutron lifetime still needs resolution [2], and tension has recently surfaced between extractions of λ as the two competing techniques, using the beta-asymmetry A or the electron-neutrino correlation a, have reached high precision (Table 1). The most precise determinations of λ from the beta-asymmetry and electron-neutrino correlation disagree by about $3\,\sigma$. A nonzero Fierz term is one intriguing possible explanation for the disagreement, where a combined fit of the two high-precision results of PERKEO III and aSPECT gives $b = -0.0181 \pm 0.0065$ and $\lambda = -1.2724 \pm 0.0013$ [7].

Table 1: Recent determinations of λ

Experiment	Correlation	Result	Fierz limit
PERKEO III	A	$\lambda = -1.27641 \pm 0.00056$ [8]	$b = 0.017 \pm 0.021$ [9]
UCNA	A	$\lambda = -1.2772 \pm 0.0020$ [10]	$b = 0.066 \pm 0.048$ [11]
aCORN	a	$\lambda = -1.2712 \pm 0.0061$ [12,13]	
aSPECT	a	$\lambda = -1.2668 \pm 0.0027$ [7]	$b = -0.0098 \pm 0.0193$ [7]

Future improvements to λ using the beta-asymmetry are proposed by UCNA+ (0.05%) [3], pNab (0.02%) [3], and PERC (0.01%) [14]. For the neutron system to be competitive with the Superallowed Fermi decays, it is imperative that not only the precision in λ be improved but also the tension resolved. To our knowledge, the only experiment currently pursued to remeasure the electron-neutrino correlation is the Nab experiment. Nab's goal sensitivity of $\Delta\lambda/|\lambda| = 0.04\%$ will therefore provide an extremely important input for the entire neutron data set. To shed light on these hints of non-standard currents in the weak interaction, clarify the inconsistencies in the neutron dataset and improve the precision in the determination of V_{ud}, it is imperative that Nab be enabled to achieve its ultimate precision. Successful completion of Nab will lay the groundwork for the neutron to provide an independent and more precise determination of V_{ud}, free from the uncertainties of nuclear corrections.

2. Nab Experiment Approach and Status

Nab's experimental approach relates the electron-neutrino correlation to the proton's momentum as a function of electron energy, using the conservation of energy and momentum [15–18]. The precise determination of decay electron energies and the time of flight of decay protons in Nab allows the reconstruction of the full phase space for neutron beta decay for electrons above 100 keV. The asymmetric spectrometer captures charged beta decay products from the nominally unpolarized neutron beam and directs them to one of two highly segmented silicon detector systems.

Nab has already completed major milestones for experiment commissioning. The magnet was installed and characterized in 2018 and 2019. Proton detection and characterization of the detector system was demonstrated using offsite facilities in 2021. A preliminary investigation of unwanted neutron beam polarization was performed in 2022. We note an unexpected failure mode resulted in an accidental displacement of the magnet coils, creating a thermal contact which prevented cooldown, which shut down the experiment between 2022 and 2023. Despite this, after repair of the magnet, the capability of the spectrometer and all major subsystems was demonstrated in the first commissioning run in 2023 by measuring the characteristic "tear-drop" shape of the neutron beta decay phase space and comparing its consistency with prediction from simulation (Figure 1). The operational status of Nab's subsystems as of July 1, 2024 is summarized in Table 2. During the upcoming SNS accelerator cycle, commissioning of the remaining subsystems will be completed.

3. Requirements for beamtime and ORNL commitment

3.1. Request justification and assumptions

We estimate our time requirements to achieve a statistical sensitivity $\Delta\lambda/|\lambda| = 0.04\%$, or relative statistical uncertainty in the electron-neutrino correlation $\frac{\sigma_a}{a} = 7 \times 10^{-4}$, using the following basis. We are assuming the analysis will use the inner 75% events of the tear drop, an electron energy

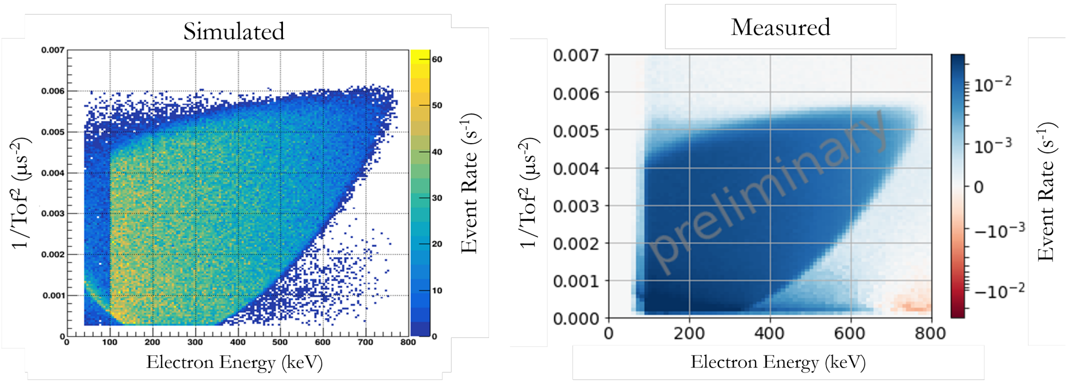

Figure 1: Simulation (left) and preliminary measurement (right) of the event rate as a function of proton time of flight and electron energy in the Nab spectrometer.

Table 2: Nab Subsystem Status

Subsystem	Status	Note
Magnet	Operating	Experienced failure and repair in 2022-2023
Polarimetry/Beamline	Commissioning	
Detector System	Commissioning	Upgrade in progress. Detector qualification in progress
Detector cooling	Operating	
Data acquisition	Operating	Full demonstration requires completion of detector system upgrades
Calibration system	Commissioning	
High voltage system	Operating	Upper system only

threshold of 100 keV, a maximum proton time of flight of 40 μs, a signal to background of 10:1, and we are fixing $b = 0$. If so, the statistical uncertainty $\frac{\sigma_a}{a}$ follows the relationship $\sigma_a = \frac{4.5}{\sqrt{N}}$ for total events N. Assuming a simulated total decay rate of 1600 cps at 1.4 MW operation and acceptance of about 1/8 of protons, we estimate 240 total days are required at full efficiency of physics data-taking to meet Nab's precision goals for the electron-neutrino correlation. Similarly, we estimate the time required to achieve an absolute statistical sensitivity of the Fierz term $\sigma_b = 10^{-3}$ from the relation $\sigma_b = \frac{16.9}{\sqrt{N}}$, for a total of 15 days. Our estimates for beamtime requirements are based on the published FY2024 and FY2025 Planning Schedules[*] and the SNS 5-Year Working Schedule[†]. We include the planned ramp from 1.4 MW to 2.0 MW operation, and assume 80% accelerator uptime due to planned and unplanned maintenance periods. These estimates do not include the anticipated dedicated campaigns for systematic studies, daily calibration, optimization of run conditions, or maintenance outages. We account for this with an estimated experiment efficiency, which ramps up

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[*] https://neutrons.ornl.gov/sns/schedule, accessed 2024-07-01

[†] https://neutrons.ornl.gov/hfir/hfir-sns-5-year-working-schedule, accessed 2024-07-01

in the periods after commissioning data-taking. To support our beamtime request, our estimate of the accumulated time towards the precision result in units of 100% efficient days is tabulated below. For clarity, we tabulate the electron-neutrino correlation and Fierz term in separate sequential campaigns. With these assumptions, we estimate that we can fulfill the time needed to reach statistical sensitivity for the electron-neutrino correlation and Fierz term (240 days and 15 days respectively) at the end of the calendar year 2026. We note that the 2024 accelerator cycle will be devoted to transitioning from commissioning to physics data-taking, with a goal to prepare a separate dataset that can reach a 1–2% sensitivity measurement, approaching that of aSPECT.

Table 3: Summary of assumptions for time to achieve Nab's precision goals. 'Beam-on days' is our estimate assuming SNS has 80% uptime. 'Power' refers to the planned SNS proton power. 'Efficiency' captures our estimate of experiment uptime for beta decay data-taking. 'Days of β data' and 'Accrued days' is the resulting size of the dataset per period and total accumulated, respectively. $(\sigma_{a/b})_{\text{stat}}$ refers to the accumulated statistical uncertainty for the electron-neutrino correlation and Fierz term, respectively. Note in 2024, the primary limitation is expected to be understanding of systematic effects, as <2% statistical uncertainty is achievable in less than one day.

Period	Beam-on days	Power	Efficiency	Days of β data	Accrued days	
Data-taking for electron-neutrino correlation						$(\sigma_a)_{\text{stat}}$
Jul-Nov 2024	105	1.7 MW	*	*	*	$<2\times10^{-2}$
Feb-May 2025	100	1.7 MW	25%	30	30	2×10^{-3}
Aug-Nov 2025	75	1.8 MW	50%	50	80	1×10^{-3}
Feb-May 2026	100	1.9 MW	75%	100	180	8×10^{-4}
Aug-Oct 2026	60	1.9 MW	75%	60	240	7×10^{-4}
Data-taking for Fierz term						$(\sigma_b)_{\text{stat}}$
Nov 2026	15	2 MW	75%	15	15	1×10^{-3}

3.2. *Contingency*

Several of Nab's capabilities must still be demonstrated. Our beamtime estimate assumes readiness for physics data-taking in 2025, but as some key risks are outstanding, we request an additional 50% contingency in beamtime, or one year (i.e. until the end of 2027). Notable effects and associated risks are summarized below, as well as impacts relevant to beamtime and facilities.

- The impact of the magnet failure on previous characterizations of the magnet is unknown. A new campaign requires an experiment shutdown and partial disassembly which may extend further into beamtime than expected.
- We are planning a measurement to place a limit on the neutron beam polarization below

$< 10^{-5}$. More beamtime than anticipated may be required to set this limit or to demonstrate effectiveness of the spin-flipper system.

- In the 2023 dataset, the detected proton energy was much lower than expected for unknown reasons, which results in an unquantifiable systematic uncertainty. A candidate replacement detector has been identified, but is not yet demonstrated to fully resolve or avoid the issue.
- In the 2023 dataset, instabilities in the detection system electronics rendered many detector pixels unresponsive, which results in an unquantifiable systematic uncertainty. The electronics are undergoing an upgrade for improved mapping, stability, and robustness which have promising results on a small scale but are not yet demonstrated for the full system.
- Commissioning of the electrode system and a lower high voltage system required for the Fierz search is still needed.
- The SNS ramp-up to higher power may result in more downtime than has been experienced historically, and ramp to maximum power may be delayed or limited.
- Operations funds are expected to be reduced in 2025 compared to prior years. Further reduction in funding or unreliable delivery of funds will delay precision physics data-taking.

The beamtime estimates above assume that Nab has exclusive use of the 13A and 13B beamlines. Use of the full calibration system, needed to reach all detector pixels, interferes with the 13A beamline. We note that with careful planning and coordination, Nab can operate simultaneously with 13A, though possibly with reduced efficiency. The main impacts of 13A operation on Nab are (1) limited view area of the calibration system during data-taking, (2) reduction of beam intensity and unknown impact on polarization due to insertion of beamline 13A components, and (3) access limitations during 13A operation for radiological safety. The possible reduction in efficiency and physics sensitivity from these effects has not been fully evaluated. However, even in a worst-case scenario, beamtime sharing can be implemented strategically to perform specialized systematic studies, and allows catch-up of analysis input. A beam-sharing compromise could be accommodated with corresponding flexibility of the experiment termination date.

3.3. ORNL commitment

As a medium scale experiment, Nab requires significant commitment from the ORNL scientific staff to meet its goals in a timely fashion. Technical coordination of various onsite experiment activities within Nab and with other experimental efforts must be carefully planned for efficient use of beamtime. The polarimetry and magnetometry campaigns will require safety calculations, engineering support, and working closely with SNS Facility and Operations teams. The detection system will require scientific support to develop an onsite detector qualification program and continued electrical and mechanical engineering support to improve robustness of the system. The calibration efforts require close coordination with radiological safety. Computing and management of the very large datasets must comply with ORNL policies. Technical and engineering support is needed for experimental operations, upgrades, and maintenance. Administrative support is needed for management of the operating budget at ORNL. Finally, due to the experiment duration, the onsite visiting students would benefit greatly from the scientific staff's onsite support of their technical work and research.

4. Summary

The Nab experiment, now commissioning at the SNS, aims to perform the world's most precise measurement of the electron-neutrino correlation and most stringent limits on a possible Fierz term in neutron beta decay. The project has successfully demonstrated the capabilities of the experiment during its 2023 commissioning run, and is poised to begin physics data-taking during the upcoming 2024 accelerator cycle. To ensure Nab can meet its physics goals, we request use of the 13A and 13B beamlines for two full years of precision physics data-taking plus one additional year for contingency. This request will allow Nab to achieve its ultimate precision and meet its goals to provide critically needed input on the tension in neutron dataset, enable improved precision in the CKM unitarity test, and allow greater understanding of the weak interaction.

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