Proposal update for the n-^{3}He experiment

A Measurement of the Parity Violating Proton Asymmetry in the Capture of Polarized Cold Neutrons on ^{3}He

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1. Introduction

This is an update to the n-^{3}He PV experiment proposal, "A Measurement of the Parity Violating Asymmetry in the Capture of Polarized Cold Neutrons on ^{3}He," [1] presented to PRAC in 2008. This update includes a technical plan of the experiment with cost, funding profile, and a schedule with main milestones. The goal of this experiment is to accurately measure the proton asymmetry in the reaction $\vec{\mathrm{n}} + {}^3\mathrm{He} \rightarrow \mathrm{p} + \mathrm{T}$. This experiment will use much of the NPDGamma experimental setup, making it relatively easy to construct and set up. The two main differences between the n-^{3}He and NPDGamma experiments are: a) the target/detector, and b) running with longitudinal polarized neutrons in an effort to control systematic uncertainties. As shown in Fig. 1, the major new pieces of hardware are: a) a 10 G solenoid for the longitudinal holding field, b) a longitudinal RF spin rotator, and c) the combined ^{3}He target / detector ion chamber.

2. Technical Feasibility

Several new developments have put the technical feasibility of the n-^{3}He experiment on firmer ground. A new four-body calculation of the PV asymmetry has determined the

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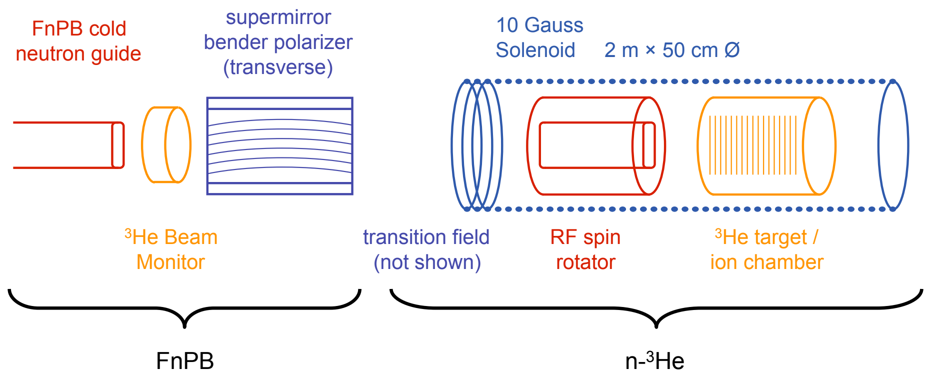

Figure 1: The n-^{3}He experimental setup including existing equipment at the FnPB from the NPDGamma experiment: the supermirror polarizer and 3He beam monitor. The radiological shielding build for the NPDGamma experiment doesn't need to be modified for the n-3He experiment. Also the magnetic shielding of the NPDGamma will be used.

sensitivity of the n-^{3}He PV asymmetry to different isospin contributions of the hadronic weak interaction at low energies. Measurements of the beam flux at the FnPB have confirmed the projected neutron flux and thus the expected statistical accuracy is achievable. Further investigations of systematic errors have confirmed the need to run the experiment with longitudinal polarization, leading to physically realizable specifications of each apparatus.

2.1. *Statistical Sensitivity*

A major development in the n-^{3}He experiment since approval at the last PRAC meeting is first full calculation of the PV asymmetry $A = 3 \times 10^{-7}$ using full 4-body wave functions by the Michele Viviani *et al.* at I.N.F.N, Pisa [2]. The calculation is still preliminary, but results are consistent with the estimate of Gudkov presented in the n-^{3}He proposal. Their calculation was done within the DDH meson exchange framework, and they are working on extending the calculation to the EFT framework. The sensitivity to each DDH coupling coefficient is

$$A_y = -0.1821 h_\pi^1 - 0.1447 h_\rho^0 + 0.0267 h_\rho^1 + 0.0012 h_\rho^2 - 0.1269 h_\omega^0 + 0.0495 h_\omega^1 \tag{1}$$

In the DDH framework, the n-^{3}He experiment is an important PV measurement because it is an independent probe of the HWI couplings. We only need to consider the four couplings h_π^1, h_ρ^0, h_ρ^2, h_ω^0, since the short-range $\Delta I = 1$ couplings are small and have a very narrow DDH reasonable range. At present there are four independent PV experiments: the ^{18}F measurement of h_π^1, the odd-proton nuclear measurements, and elastic p-p scattering at two different energies. The NPDGamma experiment will measure h_π^1, providing an independent check of the ^{18}F measurement. With NPDGamma and the elastic p-α asymmetry as one of the odd-proton nuclei, we will have four independent measurements in few-body systems, without the complication of nuclear structure. In order to test the predictive power of the DDH model, an overdetermined system is needed with a fifth independent experiment, such as n-^{3}He. Table 1 shows the increased sensitivity to these four couplings from the n-^{3}He asymmetry.

f_π	h^0_ρ	h^2_ρ	h^0_ω	description
4.6	-11.4	-9.5	-1.9	DDH Best Value ($\times 10^{-7}$)
0.0–11.4	-30.8–11.4	-11.–7.6	-10.3–5.7	DDH Reasonable Range
8.1%	15.8%	77.2%	36.4%	present / DDH Range (%)
5.8	14.0	64.7	36.4	present + npdγ
3.3	13.8	30.6	35.0	present + n^{3}He
3.1	13.4	30.3	34.0	present + npdγ + n^{3}He
8.2	24.6	132.6	36.4	present few body + npdγ
6.7	14.9	33.0	35.8	present few body + npdγ + n^{3}He

Table 1: The uncertainty in each coupling as a percentage of the DDH reasonable range, including various experiments. 'present' refers to the presently available experimental data. The last two lines include only few-body observables.

Since the proposal, measurements of the neutron flux at the FnPB have confirmed the numbers used to predict the statistical sensitivity. The projected statistical error after running for 2775 hours of beam, corresponding to a one year beam cycle when efficiencies are included, is

$$\delta A = \frac{\sigma_d}{P\sqrt{N}} = \frac{6}{0.96\sqrt{2.2 \times 10^{10}\ \text{n/s} \ \cdot \ 10^7\ \text{s}}} = 1.3 \times 10^{-8} \tag{2}$$

2.2. *Systematic Errors*

Systematic errors should be controlled at least one order of magnitude better than the statistical error. Possible contributions to the systematic uncertainty have been catalogued by considering all combinations for Cartesian invariants formed from vectors present in the system. They are listed in table 2.

Invariant	Parity	Size	Comments
$\vec{\sigma}_n \cdot \vec{k}_p$	Odd	3×10^{-7}	Nuclear capture asymmetry
$\vec{\sigma}_n \cdot (\vec{k}_n \times \vec{k}_p)$	Even	2×10^{-10}	Nuclear capture asymmetry
	Even	6×10^{-12}	Mott-Schwinger scattering
$\vec{\sigma}_n \cdot \vec{B}$	Even	1×10^{-10}	Stern-Gerlach steering
	Even	2×10^{-11}	Boltzmann polarization of ^{3}He
	Even	4×10^{-13}	Neutron induced polarization of ^{3}He
$\vec{\sigma}_n \cdot \vec{k}_n$	Odd	1×10^{-11}	Neutron beta decay

Table 2: Cartesian invariants and their associated systematic uncertainties.

The dominant systematic uncertainty results from an admixture of the parity even $\vec{\text{n}} + {}^3\text{He} \rightarrow \text{p} + \text{T}$ nuclear capture asymmetry. This asymmetry, proportional to $\sigma_n \cdot k_n \times k_p$, would appear as a left/right (L/R) asymmetry considering the PV up/down (U/D) asymmetry $\sigma_n \cdot k_n$ is measured with transverse polarized neutrons. Gerry Hale performed an R-matrix fit to this asymmetry using nuclear structure and resonance properties of the 4 nucleon system. At very low energies it goes like $-\sin(\theta)$, so the maximum in magnitude is at 90° (c.m.). The analyzing-power can be well approximated by

$$A_y(90^\circ) = -(1.7 \pm 0.3) \times 10^{-5}\sqrt{E/\mathrm{eV}} \tag{3}$$

At our beam energy of 10 meV, $A_y(90^\circ) = -1.7 \times 10^{-6}$, two orders of magnitude greater than the statistical sensitivity of the PV measurement. With transversely polarized neutrons, the PC asymmetry would mix at the level of $\sin(\theta)$, the misalignment angle of the detector wire planes with respect to the holding field, making suppression extremely difficult. Thus the experiment must be done with longitudinal polarized neutrons, yielding an extra suppression factor of $\sin(\theta')$ the misalignment angle of the beam direction with respect to the holding field. So the experiment is designed with σ_n, k_n, and k_p all parallel. Now the alignment requirements are modest: the holding field, beam direction, and detector wire planes must each be aligned to within 10 mrad. This will suppress the PC asymmetry by a factor of 10^4, about 60 times smaller than the statistical goal. This is reasonably achievable using standard machining tolerances and standard survey technology.

Mott-Schwinger scattering is another contribution to the PC asymmetry $\sigma_n \cdot k_n \times k_p$. The calculated analyzing power for ^{3}He elastic scattering at 90° is $A_{MS} = 5 \times 10^{-4}$. The capture cross section is 8.4×10^3 barns and the elastic scattering cross section is 2.3 barns. MS scattering manifests itself if the neutron scatters elastically before capturing. The probability of elastic scattering is $W = 2.7 \times 10^{-4}$. The mean free path of a 10 meV neutron is $\lambda = 1/n\sigma = 4.4$ cm. The beam moves to the L/R by $dx = \lambda A_{MS} W = 6 \times 10^{-7}$ cm. One can estimate the size of the L/R asymmetry by dividing by the beam size, about 10 cm. The L/R asymmetry is then 6×10^{-8}, which is small compared to the parity even capture asymmetry, $A_y = -1.7 \times 10^{-6}$.

The dominant Stern-Gerlach effect for longitudinal neutrons is to change their velocity and therefore absorption cross section in a spin-dependent manner. The change in neutron kinetic energy equals the change in $\vec{\mu}_n \cdot \vec{B}$ between the exit of the spin flipper and capture in the ^{3}He. From the $1/v$ dependence of the cross section and requiring $\delta A = \delta\sigma/\sigma = \delta\vec{\mu}_n \cdot \vec{B}/2E_n < 1 \times 10^{-10}$, the holding field strength must be uniform to the level of $\delta B < 300$ mG between the spin flipper and target, that is, to the 3% level.

The magnetic fields could also polarize the ^{3}He, resulting in a large spin-dependent cross section. At room temperature in the 10 G holding field, the thermal polarization would be $P_3 = \tanh(\exp(-\vec{\mu}\cdot\vec{B}/kT)) = 2.5 \times 10^{-9}$, four times smaller than the statistical goal. By reversing the holding field, the physics asymmetry will stay the same, but the double-spin asymmetry will reverse. We require the asymmetry in the reversed magnetic field to be less than 1% in order to control this systematic error two orders of magnitude below statistical sensitivity.

The polarized neutrons will also polarize the ^{3}He due to the highly spin-dependent absorption cross section. For the most part this does not induce a false asymmetry because the polarization follows the neutron spin state leading to the invariant $\sigma_n \cdot \sigma_n = 1$. However, asymmetry in the beam polarization due to the spin flipper efficiency will induce a constant polarization, again in the direction of the holding field. This is another effect associated with the invariant $\sigma_n \cdot \vec{B}$. The magnitude of polarization is $(\phi t_1)/(A/\sigma) =$

$(2.2 \times 10^{10}$ n/s $\cdot$ 1 hr)/(10 cm $\cdot$ 12 cm/5300 b) $= 3.5 \times 10^{-11}$, smaller than Boltzmann polarization.

Neutron beta decay in the target is a parity odd observable which could mimic the physics asymmetry. For 10 meV neutrons, the probability of decay inside a chamber 20 cm long is 1.6×10^{-7}. The neutron spin-electron momentum correlation is $A \; -0.1$. The electrons are minimum ionizing particles, and the proton energy is suppressed by a factor of $m_p/m_n \approx 2000$. Thus the beta decay contribution will be $\delta A \approx 10^{-11}$. The contributions from activation and beta decay of aluminum and other materials are likewise small. Also, the ionization chamber is insensitive to gamma asymmetries such as the material false asymmetries encountered in the NPDGamma experiment.

In summary, the technical requirements in order to control our systematic errors are given in table 3.

Property	Specification
Magnetic holding field	10 G
Field gradient (^{3}He neutron polarimetry)	5×10^{-4}/cm
Field uniformity (position)	3%
Field uniformity (reversal)	1%
Field uniformity (angle)	10 mrad
Drift chamber wire plane alignment	10 mrad
Neutron beam direction alignment	10 mrad

Table 3: Specifications of fields and alignment.

3. Updates in Experimental Design

3.1. Holding Field Solenoid

As shown above, the requirements for the holding field solenoid are quite modest. The coil is be a 2 m long 0.5 m diameter solenoid with extra windings at the end for the fringe field, and an approximate current density of 8 A/cm. Using standard 10 gauge magnet wire with 2.5 mm winding pitch (2.5 km $\cdot$ 3.2 Ω/km), it would require about 32 W. The design must produce uniform fields to 10 mrad.

3.2. RF Spin Rotator

A new method for designing the spin flipper has allowed us to improve the experimental setup with a much more compact form factor. The RFSF is different from the NPDGamma spin flipper because it must rotate longitudinal instead of transverse polarized neutrons. Thus a transverse RF field is need to 'tumble' the neutrons in the forward direction as opposed to rotating them around the side. The 2008 proposal proposed a double racetrack design with two toroidal solenoids to amplify the RF and minimize gradients. However this design had a large cross sectional area and would have be difficult to implement.

It was realized that the same principle could be used in a compact design with the appropriate use of surface currents to shape the fields instead of relying on geometry alone. The method of calculating the require currents to produce a uniform RF spin flipper field in the region of the neutron beam is detailed in Ref. [3]. Using this method, a spin flipper was designed using the same cylindrical form factor as the NPDGamma spin flipper. From the calculated inductance, and resistance of the coil, this design is well matched to the RF power requirements of the NPDGamma spin flipper. Thus the RFSF can use the same driver electronics as the NPDGamma system, just with a new resonator. This is not a surprise considering the similar volume and RF amplitude specification of the two spin rotators. The key difference in the windings is illustrated in Fig. 2. The NPDGamma coil is wound as a solenoid producing longitudinal fields, while the n-^{3}He coil is wound more like a $\cos\theta$ coil. It produces transverse (left-right) fields which loop back around either over or under the neutron beam. Thus the double-racetrack field shape is maintained, but in a much more compact geometry. The calculation of the winding pattern and RF fields produced is also shown in Fig. 2.

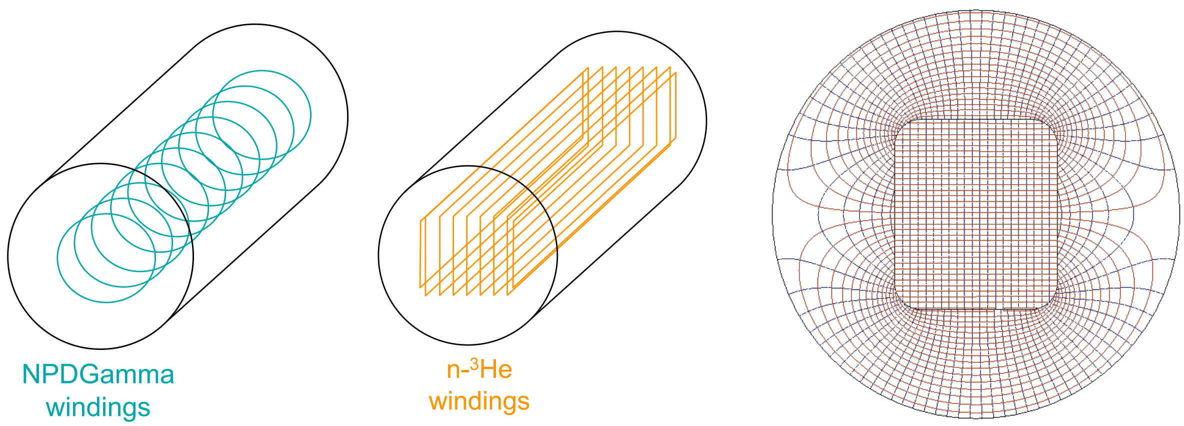

Figure 2: a) A comparison of windings of the NPDGamma RFSF solenoid (left) and the n-^{3}He coil (right). b) The winding pattern as calculated in COMSOL. The double racetrack field lines are shown in blue, while the end-cap windings are shown in red. The windings extend longitudinally down the RFSF cylinder along the outside and along the inner square.

A prototype RFSF has been built at the University of Kentucky and is being tested with RF power. It was built using experience gained in designing a nonmagnetic holding field for the neutron guide entering the cryostat of the nEDM experiment[4], with strict field requirements.

3.3. ^{3}He Ion Chamber

For a general overview of the operating conditions, requirements and general design criteria of the target chamber, we refer the committee to our first PRAC proposal from January 2008 [1]. Here, we will provide specific details about new design decisions and prototype test results.

Figure 3 illustrates the wire layout as well as several facts with regard to the proton-triton dynamics and relative signals. Figure 4 shows the design drawing for the proposed wire chamber. This design was submitted for quote to Atlas Technologies and is priced at \$US 23,799 US, with aluminum neutron windows ($\lesssim 0.9$ mm thick). The chamber has an inner diameter of 10 inches and an inner length of about 12 inches. The use of aluminum is desired to cut down on the background from neutron interaction with the chamber walls and to remove any possibility for magnetization and consequently neutron depolarization and steering. For example, the neutron capture cross section for aluminum is 2 orders of magnitude smaller than it is for stainless steel.

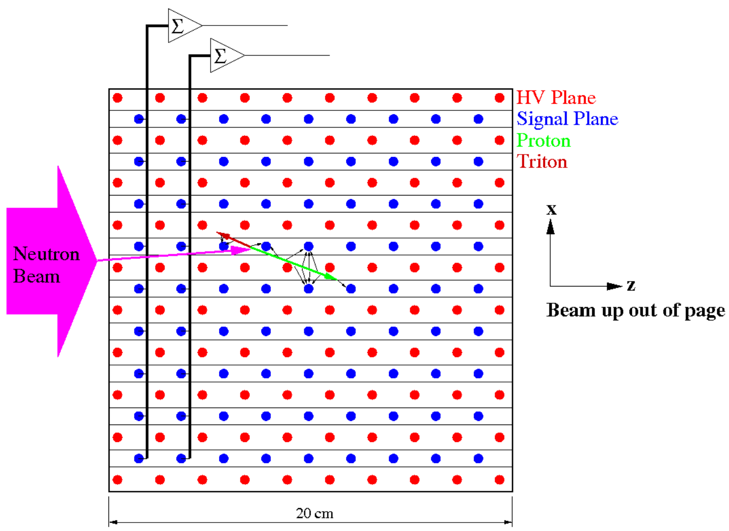

Figure 3: Initial design possibility for the target wire chambers.

The efficiency of the wire chamber depends in a complicated way on the proton angles, neutron energy, and wire plane spacing. The overall efficiency of the detectors σ_d will enter into the error on the physics asymmetry (see Eqn. 2). The energy deposition by the proton and triton varies, based on where the neutrons capture. The spacing, position and number of wires was carefully chosen to minimize the additional error due to detector efficiency. Based on the simulations and calculations performed for the first PRAC proposal [1], there are 400 signal wires that must be read out individually through the ports shown in the drawing. The largest density of signal wire readout is 50 per port/feedthrough. The chamber therefore requires 8 signal readout ports, as well as two gas circulation ports and two high voltage ports. The active volume of the chamber will be about 16 cm $\times$ 16 cm $\times$ 30 cm. The chamber must be large enough to allow the protons to range out completely. In a chamber filled with one atmosphere of helium 3, the neutron mean free path is about 2.5 cm, while the proton range peaks between 3 cm and 8 cm, depending on the amount and type of quench gas. For the purpose of measuring longitudinal asymmetries, the optimum sensitivity is reached when the neutron mean free path is small compared to the range of the proton.This is achieved by filling the chamber mostly with helium 3 ($\approx 98\%$) with as small a fraction of quench gas as possible. A small fraction of quench gas is required to maintain an adequate ionization signal.

Figure 5 shows an engineering drawing (left) and the pieces for one of the new beam monitors that are to be used that the SNS FnPB, as constructed by Atlas Technologies. The design of the beam monitors is identical to that of the proposed n-^{3}He chamber. It

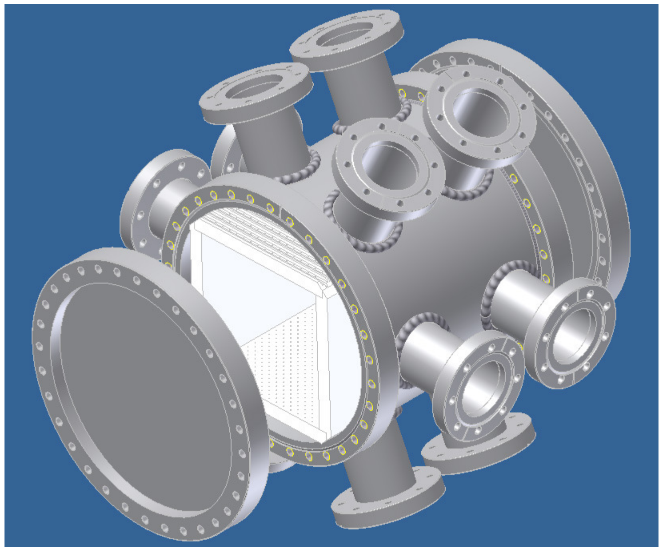

Figure 4: Chamber design for the n-^{3}He target/detector.

essentially incorporates one full wire plane, as it would be used in the n-^{3}He chamber, except with larger wire spacing and lower ^{3}He density. Between December 2008 and June 2009, a set of tests was performed with the new beam monitor, which was constructed at the University of Manitoba. Analysis is still in progress, but a counting statistics analysis as well as a long term gain/signal stability test indicate that the design can be used to operate this type of ion chamber with low noise and without gain loss over long periods of time.

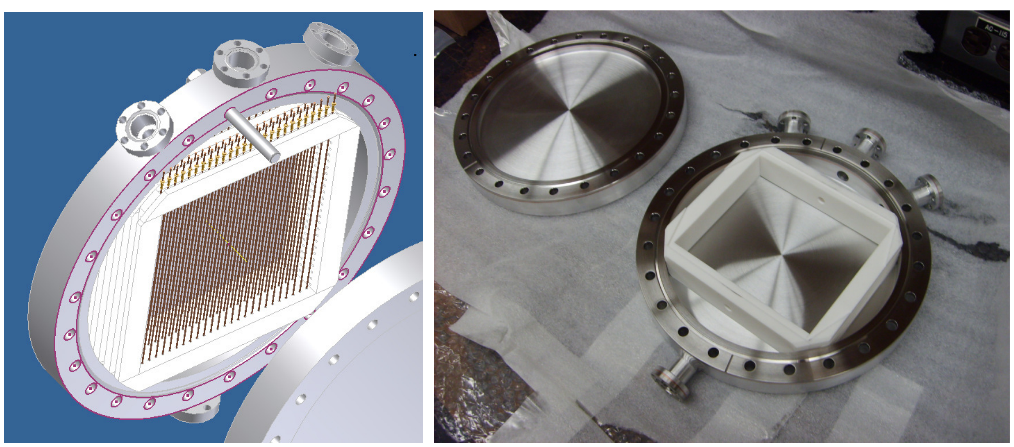

Figure 5: First of the three neutron beam monitors under construction.

The wire frame, seen in white, is made from Macor, a machinable glass ceramic (mostly alumino-silicate), which has extremely good electrical insulator properties, is heat resistant, thus allowing bake-out, rigid, and contains materials that provide the lowest source of background under interaction with neutrons. The frame has 200 micron copper traces deposited on the outside (not visible in the figure), to facilitate the signal readout and HV supply.

This was done at the University of Manitoba Nano Fabrication Facility, within the Electrical Engineering Department. The facility is capable of putting complicated electronic circuit designs on Macor.

We will be using similar wire frames for the n-^{3}He chamber. The machining of Macor is problematic and time consuming without CNC machines and proper ventilation and exhaust equipment. The cost for the wire frames therefore includes not only the material for the target/detector chamber, but also the machining costs for the more complicated parts. The wire frames can be purchased through Morgan Advanced Ceramics, machined to an accuracy of up to 0.001 inches. About 825 relatively thick (for a wire chamber) 0.2 mm, copper wires will be pulled across the frame. The material of the wire was chosen to minimize the interaction with neutrons and the thickness was chosen to combat the non-linearity inherent in the electron avalanching (gain increase) process that takes places for very thin wires, due to the concentration of field lines near the wire. The n-^{3}He chamber is a current mode detector, in that individual neutron events cannot be resolved, due to high neutron rates. Therefore, the gain increase from thin wires, which is usually desired when one builds wire chambers for pulse counting and or tracking experiments, is not needed and the non-linearity causes more problems than the benefits of gain increase.

Each of the 400 signal wires in the n-^{3}He target/detector chamber must be read out and amplified individually before further processing the signals. This provides separate signal information for each active cell in the chamber, defined by one signal and the four surrounding high voltage wires. This is needed to obtain maximum efficiency in the asymmetry measurement. The kind of amplifier that is needed is routinely manufactured at TRIUMF for a variety of experiments. The quoted cost of $CAD 35 per channel was obtained from the TRIUMF electronics shop and is based on the current prices for the electronic components.

4. Organization, Cost, and Schedule

The n-^{3}He experiment is divided into nine subprojects, which are listed in Table 4 with responsible institutions and participants. The collaboration effort is lead by three spokespersons: David Bowman/ORNL, Michael Gericke/Univ. of Manitoba, and Chris Crawford/UKy, an Experiment Manger (TBD), and Executive Committee (TBD). Memoranda of understanding between the participating institutions are in preparation.

	Subproject	Responsible Institution and Person	
1	Polarized beam	UVa	Stefan Baeßler
2	Spin flipper	UKy	Chris Crawford
3	Magnetic field	UNAM	Libertad Barron-Palos
4	Target/detector	UManitoba	Michael Gericke
5	DAQ system	UKy	Chris Crawford
6	Shielding/collimation	UNH	John Calarco
7	Alignment	ORNL	David Bowman
8	Operation	ORNL	Seppo Penttilä

Table 4: Top-level subproject structure, responsible institutions, and responsible persons.

A detail cost estimate for the experiment is shown in the attached spreadsheet using FY09 dollars. The spreadsheet is summarized in the following tables. Table 5 lists the estimated base cost of the task, overhead and contingency, and received funds of each subproject. Table 6 shows the expected source of funds, and Table 7 shows the planned funding profile. Finally the milestones associated with each project identified in Table 8.

	Subproject	Base Cost	Overhead	Contingency	Total	Funded
1	Polarized beam	4	3	2	9	0
2	Spin flipper	16	3	6	25	0
3	Magnetic field	45	17	18	80	25
4	Target/detector	113	6	34	153	134
5	DAQ system	94	24	31	149	0
6	Shielding/collimation	7	2	2	11	0
7	Alignment	5	3	2	12	0
8	Operation	5	3	2	12	0
	Total	298	66	97	451	159

Table 5: Estimated base costs of each subproject, calculated overhead and contingency, and received funds [k$].

	Subproject	Existing Funds	DOE Request	Other Requests
1	Polarized beam	0	9	0
2	Spin flipper	0	2	23
3	Magnetic field	25	55	0
4	Target/detector	134	19	0
5	DAQ system	0	30	119
6	Shielding/collimation	0	11	0
7	Alignment	0	12	0
8	Operation	0	12	0
	Total	159	150	142

Table 6: Requested funding from DOE and other sources [k$].

5. Summary

Critical progress has been made towards realizing the n-^{3}He experiment, including new theoretical calculations and refinements in the design of the experimental apparatus. It is well suited to follow the NPDGamma experiment, and will make extensive reuse of NPDGamma hardware. This helps to make the n-^{3}He experiment inexpensive compared to other hadronic parity violation experiments. It can be constructed on a short timescale, and has the potential to publish new physics results by 2013. International collaborators have secured a significant fraction of the equipment funds required, which makes this experiment even more cost effect for DOE.

References

1. n-^{3}He 2008 PRAC Proposal:
`http://www.pa.uky.edu/ crawford/pub/n3he_proposal_sns.pdf`
`http://www.physics.umanitoba.ca/~mgericke/n3He/Proposal.pdf`

	Subproject	FY09(funded)	FY10	FY11	FY12
1	Polarized beam	0	4	5	0
2	Spin flipper	0	0 (+23)	2	0
3	Magnetic field	0	18	37	0
4	Target/detector	0	0	19	0
5	DAQ system	0	0 (+119)	30	0
6	Shielding/collimation	0	0	11	0
7	Alignment	0	0	12	0
8	Operation	0	0	12	0
	Total	0	22 (+142)	128	0

Table 7: Planned funding profile [k$]. Requests from sources other than DOE and added in parentheses.

2. M. Viviani, private communication.
3. C.B. Crawford, Y. Shin, "A method for designing coils with arbitrary fields," technical note, 2009-05-24. `http://www.pa.uky.edu/ crawford/pub/dsctc.pdf`
4. C.B. Crawford, Y. Shin, "Calculation of the optimal taper in the holding field of the nEDM neutron guide," technical note, 2009-05-24. `http://www.pa.uky.edu/ crawford/pub/guide_taper.pdf`

Subproject	Milestone	Date
2a	RFSF resonator designed	Jan 2010
2b	RFSF resonator constructed	July 2010
2c	RFSF tested with polarized neutrons	Dec 2010
3a	Magnetic system designed	April 2010
3b	Solenoid constructed	Jan 2011
4a	Finished chamber design	Dec 2009
4b	Finished wire frame design and wire trace layout design	Mar 2010
4c	Chamber procured through Atlas Technologies	Mar 2010
4d	Completion of procurement for all parts	Sept 2010
4e	Completion of wire frame parts	Sept 2010
4f	Completion of wire frame assembly with wires	Mar 2011
4g	Completion of chamber assembly and testing	June 2011
5a	DAQ system components procured	July 2010
5b	DAQ software written and tested on bench	Jan 2011
1a	Initial neutron polarization measurement	June 2011
1b,7a	Measurement of neutron beam angle	June 2011
3c	Solenoid installed	July 2011
3d,7b	Initial field mapping	Aug 2011
4h,7c	Chamber installed and surveyed	Sept 2011
6a	Shielding installed	Sept 2011
8a	Experiment installed, ready to commission	Oct 2011
8b	Data taking for transverse polarization	Nov 2011
8c	Data taking for longitudinal polarization	Jan 2012
8d	Completion of data-taking	Dec 2012
1c	Final neutron polarization measurement	Dec 2012
8e	Data analyzed and published	Dec 2013

Table 8: Project milestones. Independent subsystem construction milestones are grouped by subsystem, followed by interdependent milestones during integration and data taking at the FnPB.