Letter of Intent/ Initial Proposal for FnPB at SNS

Precision Measurement of A_γ in $\vec{n} + p \rightarrow d + \gamma$

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August 24, 2005

Abstract

We propose to measure the parity-violating directional γ-ray asymmetry A_γ in the $\vec{n} + p \rightarrow d + \gamma$ reaction to a precision of 1×10^{-8} in order to provide a sensitive test of models of the hadronic weak interaction. The range of predicted values of A_γ from the effective meson exchange model of Desplanques, Donoghue and Holstein (DDH) is $(0 \rightarrow -12.4) \times 10^{-8}$, with a "best value" prediction of -5×10^{-8}. The asymmetry depends almost exclusively on the weak pion-nucleon coupling f_π, with negligible model uncertainty in the interpretation of the measurement; thus, our proposed experiment will provide an unambiguous determination of the weak pion-nucleon coupling f_π to a precision of ± 20 % of its theoretically expected value. The measurements described here constitute the second phase of an established experiment that is being commissioned at LANSCE and is scheduled to acquire the first hydrogen asymmetry data in 2005. The higher neutron flux available at the SNS will enable us to make a significantly more precise measurement than is currently feasible at LANSCE.

In order to achieve a measurement of A_γ to a precision of 1×10^{-8}, we require approximately 7000 MWh of running for data collection and systematics studies. In addition, we will require approximately 1000 h of beam time at greater power than 0.14 MW for commissioning and tune up of the apparatus.

1 Introduction

The parity-violating (PV) asymmetry A_γ in the $\vec{n} + p \rightarrow d + \gamma$ reaction isolates the $\Delta I = 1$ part of the hadronic weak interaction [1]. Detailed calculations using the DDH weak potential and the well-known properties of the deuteron exhibit contributions from the heavier $\Delta I = 1$ couplings (*i.e.* ρ and ω exchange) which are less than 1% of the contribution from the pion. Moreover, the theoretical uncertainty in the relationship between A_γ and f_π^1 as recently calculated using modern strong-interaction potentials is $2 - 4\%$ [2]. Thus, a precision measurement of A_γ can accurately reveal the strength of the weak pion contribution and reduce the statistical and theoretical uncertainty in the value of f_π^1.

The pulsed beam of the Fundamental Neutron Physics Beamline (FnPB) at the SNS will be collimated to about a 10 cm diameter circle, polarized by transmission through a transversely polarized ^{3}He neutron spin filter, and flipped by a resonant RF spin flipper before interacting with the liquid para-hydrogen target. The 2.2 MeV γ-rays from neutron capture in hydrogen will be detected by an array of 48 CsI detectors. The entire apparatus is immersed in a 10 G uniform vertical magnetic field. The parity-odd component in the differential cross section produces an angular distribution of γ-rays $A_\gamma \cos\theta_{\sigma\cdot k}$, where $\theta_{\sigma\cdot k}$ is the angle between the neutron spin σ and the photon momentum k. $A_\gamma = -0.11 \times f_\pi^1$, and if the theoretical "best value" of f_π^1 is used then $A_\gamma = -5 \times 10^{-8}$ [2]. The current experimental limit $|A_\gamma| < 2 \times 10^{-7}$ is based on a measurement done at ILL [3].

The $\vec{n} + p \rightarrow d + \gamma$ experiment has been commissioned on FP12 at LANSCE and is preparing its first measurement of A_γ, which will achieve a statistical uncertainty of 1×10^{-7} in the first 400 h of beam time. A great deal of instrumentation development, study of the performance of the apparatus, and assessment of statistical and systematic uncertainties has taken place at LANSCE. All parts of the apparatus, except for the liquid-hydrogen target, have been demonstrated at close to or better than their design specifications. The liquid hydrogen target infrastructure is being installed at the present time.

After completing the run at LANSCE we propose to move the $\vec{n} + p \rightarrow d + \gamma$ experiment to the SNS and measure A_γ with an uncertainty of 1×10^{-8}. The measurement will determine f_π^1, the weak pion-nucleon coupling, with an error of 1×10^{-7}. The theoretically expected range of f_π^1 is $(0 \rightarrow 11.4) \times 10^{-7}$ [4]. The determination of f_π^1 from the measurement is free of theoretical uncertainties from many-body nuclear calculations.

2 Motivation

The hadronic weak interaction between nucleons is currently modeled in the effective meson exchange approach of Desplanques, Donoghue, and Holstein (DDH) using seven weak meson-nucleon coupling constants for the π, ρ, and ω mesons [4]. Although, there are other models, in particular a recent effective field theory (EFT) approach [5] which provides an alternative framework for analyzing the results of PV experiments, all models include a term associated with weak pion exchange. The weak pion exchange is the longest-range and, therefore, most model-independent component of the weak N-N interaction and it is the contribution that is most likely to be calculable in QCD models (two calculations exist [6, 7] and a third is in progress [8]) and eventually directly from QCD itself [9]. Four of the DDH couplings, f_π^1, h_ρ^0, h_ρ^2, and h_ω^0 enter into the expressions for parity-violating observables with large enough coefficients to be experimentally accessible. The observables include circular polarization of γ-rays emitted by unpolarized nuclei, longitudinal spin asymmetries, neutron spin rotation, γ-ray emission–spin asymmetry, and nuclear anapole moments. Because in any approach (DDH, EFT, partial wave description) the weak amplitudes are difficult to calculate, they must be experimentally determined. In addition, since a quark-level description of the hadronic weak interaction involves the exchange of W and Z bosons with ranges of 0.002 fm, the measured couplings may be a window into short range correlations between quarks.

There is a number of experimental results for PV observables from two-body (neutron-proton and proton-proton), light nuclei, heavy nuclei, and anapole moment measurements. The results are summarized in Ref. [10]. For example, the various PV asymmetry measurements in scattering of polarized protons on hydrogen determines an energy dependent linear combination of ρ and ω couplings but are insensitive to weak π-exchange. The weak pion-nucleon coupling f_π^1 has been sought by measurements of P_γ, the circular polarization of the 1081 keV γ-rays from ^{18}F. The experimental result, $P_\gamma = 1.2 \pm 3.9 \times 10^{-4}$, sets an upper limit of $|f_\pi^1| < 1.1 \times 10^{-7}$. Recently, the nuclear spin-dependent contribution to atomic PV has been measured in ^{133}Cs and also an upper limit has been set in ^{205}Tl. This atomic PV contribution is due to the anapole moment; a parity-odd electro-magnetic moment of the nucleus that is dominated in heavy nuclei by the weak nucleon-nucleon interaction. Flambaum has argued that the ^{133}Cs anapole moment result requires a large value for f_π^1 [11], which is inconsistent with the value from the ^{18}F measurements. The proposed $\vec{n} + p \rightarrow d + \gamma$ experiment at the SNS will resolve this controversy by accurately determining f_π^1.

3 Status of the $\vec{n} + p \rightarrow d + \gamma$ experiment

In 1998, the collaboration submitted the $\vec{n}+p \rightarrow d+\gamma$ proposal to DOE [12]. Progress and results of the experiment are reported in a number of publications written by the collaboration: for example, see Ref. [13].

The $\vec{n} + p \rightarrow d + \gamma$ experiment has been mounted and commissioned on FP12 at LANSCE and at present is taking data without the hydrogen target. With an average proton current of 100 μA and the measured FP12 moderator performance [14], the $\vec{n} + p \rightarrow d + \gamma$ experiment is estimated to reach a sensitivity $|A_\gamma| < 1 \times 10^{-7}$ in the first 400 h of data taking at LANSCE.

Figure 1 is a schematic of the $\vec{n} + p \rightarrow d + \gamma$ experiment in FP12; the layout in the FnPB at the SNS will be similar. In the experiment the neutrons are polarized by a ^{3}He spin filter. The ^{3}He neutron spin filter was chosen to accommodate the large area and phase space of the neutron beam, because the filter polarizes all neutron wavelengths with predictable efficiency, and because the ^{3}He polarization can be easily reversed with respect to the magnetic holding field, thus acting as an additional neutron spin flip, which is important for studies of systematic effects. The ^{3}He polarizer can be operated in the weak 10 G guide field that is constant over the entire length of the experiment. We have operated the spin filter over periods of weeks with polarization as high as 55%.

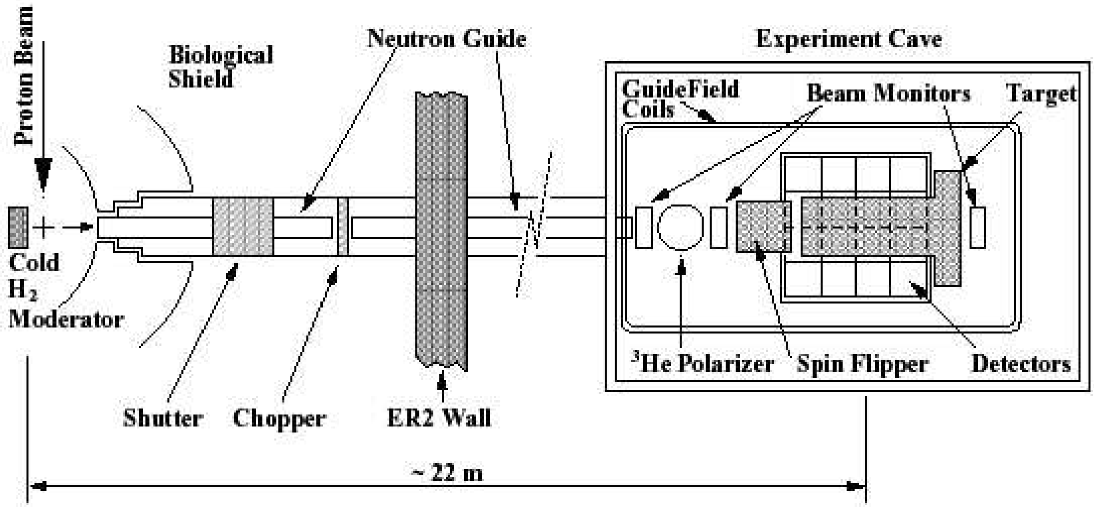

Figure 1: Layout of the $\vec{n} + p \rightarrow d + \gamma$ experiment in FP12 at LANSCE. The setup in the FnPB at the SNS will be similiar.

Two ^{3}He ionization chambers, which absorb a few % of the beam, are located upstream and downstream of the ^{3}He spin filter cell to monitor beam flux. The upstream monitor is used for normalization and the downstream monitor measures the wavelength dependent transmission through the spin filter, which allows the neutron beam polarization to be inferred.

The neutron polarization is rapidly reversed by a pulsed resonant RF spin flipper developed for the $\vec{n} + p \rightarrow d + \gamma$ experiment. The amplitude of the RF magnetic field in this spin flipper must be properly phased with respect to the pulsed neutron beam to achieve a 180^o flip for all velocities of slow neutrons in the spectrum as they arrive at the flipper. The spin flip efficiency averaged over the beam cross-section was measured to be about 98% [15].

The polarized neutrons will interact with a 20 liter liquid hydrogen target cooled to 17 K by two cryocoolers and converted to the $J = 0$ para-hydrogen molecular state by catalysts. Monte Carlo calculations show that the 30 cm diameter and 30 cm long liquid para-hydrogen target will capture about 60% of the incident cold neutron beam. To minimize neutron depolarization in the target via spin-flip scattering, the para-hydrogen concentration will be as close to 100% as possible. At 17 K the target will be greater than 99.8% para-hydrogen. At present, the LH_2 target is the only component of the $\vec{n} + p \rightarrow d + \gamma$ experiment that has not yet been commissioned. The target is under testing at LANSCE and is expected to be installed in FP12 for the data taking in late 2005.

The 2.2 MeV γ-rays from neutron capture on hydrogen are detected in an array of 48 CsI(Tl) crystals arranged in a cylindrical pattern in 4 rings of 12 detectors each around the LH_2 target [16]. In addition to the requirements of low noise operation (as close as possible to counting statistics) and suppression of systematic effects, design criteria include sufficient spatial and angular resolution, high detection efficiency, and large solid angle. Because of the high γ-ray rates, the detector is operated in current mode by converting the scintillation light from CsI(Tl) crystals to current using vacuum photo diodes. The photocurrents from the photo diodes are converted to voltages and amplifed by low-noise solid-state electronics [17]. Vacuum photo diodes are used since they are insensitive to magnetic fields. The photo current shot noise is given by $\sigma_{\text{shot}} = q\sqrt{2R_\gamma f_B}$, where q is the average amount of charge created at the photo cathode per detected γ-ray, R_γ is the average γ-ray rate, and f_B is the bandwidth, chosen to match the sample rate. In figure 2, we show a typical histogram of the detector current (converted to voltage) per pulse in a single detector, for a single spin state with a B_4C target and with the neutron beam off. The beam off data show the electronic noise, which has a width much less than 1 mV and is negligible compared to the width with beam on, which is dominated by counting statistics. The width of the beam-on distribution is 1.07 times the RMS width expected from counting statistics alone (*i.e.* $1.07/\sqrt{N_\gamma}$), where N_γ is determined from a Monte Carlo model for neutron capture on B_4C. This excess noise factor can be explained by the leakage of the 2.2 MeV γ-rays from the CsI detectors.

The $\vec{n} + p \rightarrow d + \gamma$ apparatus has measured γ-asymmetries in neutron capture on several nuclear targets in commissioning runs and in measurements that will determine possible systematic corrections for the $\vec{n} + p \rightarrow d + \gamma$ result. The targets studied include Al, B, Cl, Cu, In, Mn, Sc, and Ti. The well-known PV asymmetry in ^{35}Cl was used to verify that a nonzero asymmetry can, in fact, be measured with this setup and that the result is in agreement with the previous measurements. The Cl γ-asymmetry was also used to verify the $\cos\theta_{\sigma\cdot k}$ dependence of A_γ. The analyzed A_γ results for the nuclear targets are summarized in table 1. Tabulated errors are statistical, systematic errors are less than 10% of the asymmetries.

The targets Al, B, Cu, and In were chosen because they are materials that are expected to contribute to the γ-ray yield in the detector. The windows of the beam monitors, spin flipper, and target cryostat are aluminum and produce background, which is about 7% of the γ-detector signal. The rest of the targets have been used to study PV in polarized neutron capture on nuclei. Table 1 shows preliminary results of the asymmetry measurements with the $\vec{n} + p \rightarrow d + \gamma$ apparatus at LANSCE [18]. Both the PV up-down and parity-conserving left-right asymmetries were determined from the measurements, and except for Cl, all asymmetries are consistent with zero.

Target	Up-Down	Left-Right
Al	$(-0.02 \pm 3) \times 10^{-7}$	$(-2 \pm 3) \times 10^{-7}$
CCl_4	$(-19 \pm 2) \times 10^{-6}$	$(-1 \pm 2) \times 10^{-6}$
B_4C	$(-1 \pm 2) \times 10^{-6}$	$(-5 \pm 3) \times 10^{-6}$
Cu	$(-1 \pm 3) \times 10^{-6}$	$(0.3 \pm 3) \times 10^{-6}$
In	$(-3 \pm 2) \times 10^{-6}$	$(3 \pm 3) \times 10^{-6}$
Noise (add.)	$(2 \pm 5) \times 10^{-9}$	$(-7 \pm 5) \times 10^{-9}$
Noise (mult.)	$(3 \pm 7) \times 10^{-9}$	$(-9 \pm 7) \times 10^{-9}$

Table 1: Up-down and left-right asymmetries with their RMS widths. Only statistical errors are given. Systematic errors are less than 10% and are scaled by the asymmetry.

A conclusion of these commissioning runs is that the apparatus is ready to make an A_γ measurement with a statistical error of 1×10^{-8}. The remaining open questions are quantitative. For example, we have estimated an upper limit for the γ-asymmetry on aluminum, material used in the windows, as well as on indium and copper. Any γ-asymmetry (parity odd up–down or parity even left–right) could couple into the measurement as a systematic error. The uncertainty in the overal systematic error is currently limited by the aluminum γ-asymmetry measurement at LANSCE. We will improve

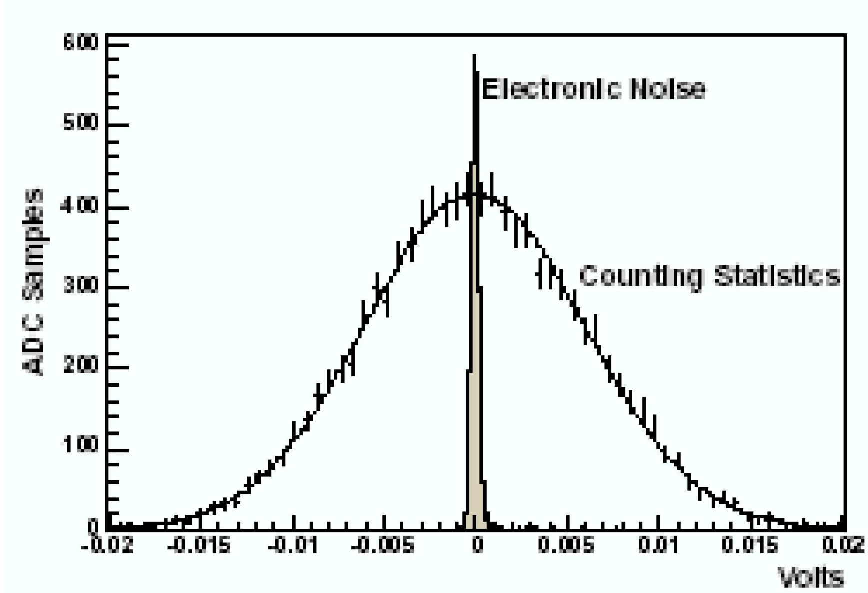

Figure 2: A typical γ-ray histogram from a B_4C target measured by one of the CsI detectors. For comparision an electronic noise histogram is shown.

this error at the FnPB so that the aluminum γ-asymmetry will make a negligible contribution to the systematic error of the $\vec{n}+p \rightarrow d+\gamma$ experiment as explained in section 5.

In summary, the $\vec{n}+p \rightarrow d+\gamma$ experiment has been set up and commissioned at LANSCE, and data have been taken with nuclear targets while waiting for the completion of the testing of the LH_2 target. We have thoroughly studied the performance of the apparatus and the beamline, and results support the conclusion that the apparatus is ready for the $\vec{n}+p \rightarrow d+\gamma$ measurement with a statistical uncertainty of 1×10^{-8}. A variety of measurements confirm that uncertainties in systematic error can be negligible; however, it will be necessary to improve the accuracy of the aluminum γ-asymmetry, verify the alignment of the detector array and the neutron polarization, and minimize background contributions at the SNS. The FP12 neutron guide is straight; thus, the observed background at LANSCE comes from the spallation target, the moderator, the guide, and the aluminum windows in the beam. Spin-independent backgrounds dilute the A_γ-asymmetry while spin-dependent backgrounds produce false asymmetries; these and other systematic issues are discussed in section 5.

4 Projections for $\vec{n}+p \rightarrow d+\gamma$ at the FnPB

4.1 The FnPB beam

The performance of the FnPB has been studied through simulations of the SNS spallation source and the beam line. The neutron flux estimates presented here are based on results of these simulations [19]. Members of the $\vec{n}+p \rightarrow d+\gamma$ collaboration together with the SNS personnel have proposed to commission the FnPB beamline including a measurement of the neutron flux. The inferred flux will permit a firm run time calculation.

Optimization of the FnPB beamline includes characterization of the guide and bender, the neutron transmission through the 0.89 nm monochromator installed for the UCN beam line, and the expected performance of the two time of flight choppers [19]. The simulations assumed the SNS power of 1.4 MW and a 10 cm $\times$ 12 cm, $m = 3.6$ super mirror guide. Our experience with the $m = 3$ supermirror guide at LANSCE, made by the same company selected to manufacture the straight section of the FnPB guide, shows that the super mirror guide performance can be accurately and predictably modeled. The simulated neutron spectrum at the FnPB was fit to an analytical function shown in figure 3 for run time estimates. For 60 Hz operation, a maximum wavelength range of $\Delta\lambda = 3.3$ Å can be used at 20 m. To avoid frame overlap, two time of flight choppers will be installed in the beamline. As discussed in section 5, possible systematic errors include contributions from spin-dependent and spin-independent neutron interactions. Knowledge of the neutron energy and polarization through a time of flight measurement and the use of two choppers will allow us to study systematic effects that have a different neutron time of flight dependence from A_γ. The choice of wavelength range shown in figure 4 maximizes the figure of merit with the simulated input spectrum for $\lambda > 2.3$ Å.

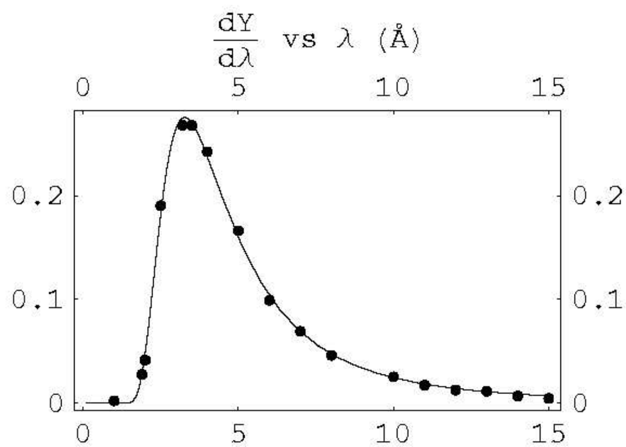

Figure 3: Predicted FnPB neutron spectrum at 1.4 MW in n/cm^2/Å/s/10^9 as a function of neutron wavelength in Å given by Ref. [19].

Our run time estimate is based on the established ^{3}He polarizer, spin flipper, γ-detector, and DAQ performance, the simulated neutron capture probability in liquid para-hydrogen, the calculated FnPB flux, and the performance of the choppers. We have considerable experience with the statistical performance of the $\vec{n} + p \to d + \gamma$ apparatus and DAQ from the commissioning runs at LANSCE. We anticipate two significant improvements at the SNS compared to LANSCE: background reduction and higher time averaged ^{3}He polarization. The $\vec{n} + p \to d + \gamma$ apparatus at the SNS will be modified to allow the installation of a 30 cm thick lead wall between the ^{3}He polarizer and the RF spin flipper to reduce the background from γ-rays produced in the source, neutron

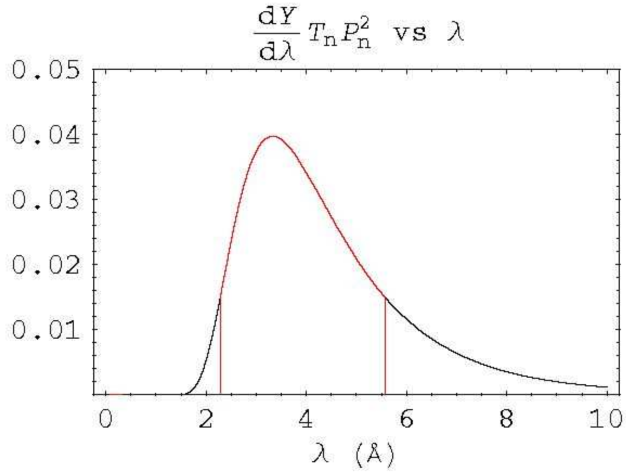

Figure 4: $\frac{dY}{d\lambda} \times P_n^2 \times T_n$ in n/cm^2/Å/s/10^9 as a function of the neutron wavelength in Å. The flux is from figure 3 and P_n and T_n are given in section 6. The red region defines the wavelength range of accepted neutrons in the frame.

guide, and ^{3}He polarizer. These γ-rays currently produce a $\sim$ 7% background in the first ring of detectors in FP12 runs at LANSCE. In the run time estimate we assume that the background is dominated by the neutron capture on aluminum windows.

4.2 Neutron polarization and flipping of neutron spin

The ^{3}He spin filter in the $\vec{n} + p \rightarrow d + \gamma$ experiment at LANSCE has achieved greater than 55% polarization, which translates to neutron polarization of $\approx$ 70 % at $\lambda = 5$ Å. A goal for the SNS will be high and stable ^{3}He polarization over long periods. The ^{3}He gas in a sealed cell is continuously polarized by spin-exchange optical pumping, currently using two 30 W fiber-coupled diode laser arrays. The extraordinarily long lifetimes of the sealed cells, typically a few hundred hours, have made it possible to obtain high polarization with modest laser power. NMR is used to monitor and reverse the ^{3}He polarization, while the measured cell transmission monitors the neutron beam polarization. The existing cells could be used at SNS; however construction of new cells to use more of the FnPB beam area may be warranted.

Although no changes to the spin filter are needed for the SNS runs, it is likely that there can be an improvement in ^{3}He polarization and thus in the statistical error of the measurement. At present, the ^{3}He polarization for the single cell that has been operated in FP12 at LANSCE has been between 40–55%, while 65% has been obtained at NIST in cells available for the $\vec{n}+p \rightarrow d+\gamma$ experiment. At NIST, it has been shown that the use of spectrally narrowed lasers can produce even 70–75% polarization in $\vec{n} + p \rightarrow d + \gamma$ cells. However, the fiber-coupled, commercial systems currently used are known to be robust for long term, unattended operation, an important issue for the reliable production running of the experiment over many months. With an appropriate engineering, it may be possible to employ spectrally narrowed lasers to substantially improve the ^{3}He polarization beyond that achieved at LANSCE. The present method of choice for spectrally narrowing high power diode laser arrays employs an external cavity with a diffraction grating. The beam polarization ^{3}He analyzer cells in the FP12 experiment at LANSCE are polarized using such a spectrally narrowed diode laser. By the time the experiment will run at the SNS, commercial approaches currently being developed could replace the external cavity and simplify the operation of a future narrowed laser. Even if no spectrally narrowed approach is deemed suitable for operation at the SNS, the ^{3}He polarization may be improved by simply increasing the broadband laser power, *i.e.* by using more and/or more powerful lasers.

The pulsed resonant RF spin flipper developed for the $\vec{n}+p \rightarrow d+\gamma$ experiment at LANSCE is versatile and effective with 98% spin flip efficiency and will be used at the SNS.

4.3 LH_2 target

The target will contain 20 liters of liquid hydrogen with more than 99.8% in the para-hydrogen state. The target will absorb about 60% of the beam according to simulations. Before the $\vec{n}+p \rightarrow d+\gamma$ apparatus is moved to the SNS, the target will be used for the initial $\vec{n}+p \rightarrow d+\gamma$ measurement at LANSCE and therefore must pass a rigorous LANL hydrogen safety review. At present, the target is undergoing offline testing including operation with hydrogen. After successful completion of the testing, the target will be installed on FP12 at LANSCE. Then the target system and its operation procedures must pass a further hydrogen safety review and the entire experiment including the target has to pass a facility readiness review. The current plan is to have the LH_2 target running on FP12 by late 2005.

To facilitate addressing the hydrogen safety issues at the SNS, a member of the SNS moderator group has been invited to join the $\vec{n}+p \rightarrow d+\gamma$ Hydrogen Target Safety Committee at LANSCE. Hydrogen safety issues at the SNS have to be addressed as soon as possible. One of the biggest construction projects for the $\vec{n}+p \rightarrow d+\gamma$ experiment at the FnPB will be the long vent stack that will safely conduct hydrogen out from the target to outside the building in both normal operation and in the event of emergencies.

4.4 Shielding

“Shielding” for the $\vec{n}+p \rightarrow d+\gamma$ experiment is used to address three distinct issues:

1. Radiological shielding required by facility requirements and ALARA considerations
2. Radiological shielding required to reduce backgrounds in the $\vec{n}+p \rightarrow d+\gamma$ detectors
3. Magnetic shielding

In the following we address each of these with reference to the experience at LANSCE as well as to the different conditions expected at the SNS.

1. Radiological shielding required by facility requirements and ALARA considerations Because the neutron guide at LANSCE is straight, the shielding requirements for the current $\vec{n} + p \to d + \gamma$ experiment are dominated by the need to attenuate a significant component of high energy neutrons ($\gg 1$ keV). Because the FnPB neutron guide is curved such that there is no line of sight to the target/moderator, the high energy neutron flux will be significantly attenuated. As a result, the dominant source term for personal radiation exposure is from the 2.2 MeV γ-rays produced in the LH_2 target. Initial MCNP estimates indicate that it will be possible to meet ORNL radiological requirements by surrounding the guide field coils by $2''$ thick steel plates.

2. Radiological shielding required to reduce backgrounds in the $\vec{n}+p \to d+\gamma$ detectors Investigations into background sources at the current experimental setup at LANSCE indicate that the dominant source of background is from neutrons either captured or scattered and subsequently captured in the upstream portions of the $\vec{n} + p \to d + \gamma$ apparatus (^{3}He polarizer, spin flipper, collimation, etc.). Because this background arises from the cold beam, we can expect similar fractional backgrounds at the FnPB. While this background is small (a few % averaged over the detector array), we intend to make minor modifications to the experimental setup at the FnPB to reduce this beam related background. In particular, the apparatus will be lengthened slightly to allow the insertion of lead shielding "walls" immediately downstream of components which have large neutron capture probabilities, and panels of ^{6}Li loaded materials will be installed in the vicinity of components that can scatter neutrons significantly.

3. Magnetic shielding The SNS has put in place a "Policy on Magnetic Interference" which effectively limits the allowable stray magnetic field variations from sample environments to levels that are similar to those expected from crane operation and other "light industrial" activities within the experimental hall. Such variations are expected to be on the order of 10–20 mG, slightly higher than the desired level of about 5 mG. Thus, some magnetic shielding will be required. The proposed radiological shield consisting of a $2''$ thick steel enclosure around the magnetic field coils will also provide a magnetic shielding factor of approximately 10. No additional magnetic shielding will be required.

5 Systematic Errors

In section 4 of the 1998 $\vec{n} + p \to d + \gamma$ proposal we discuss statistical and systematic errors in the experiment [12]. As mentioned in this LOI, the detector operates at close to counting statistics and has achieved the statistical goals given in the 1998 proposal. We divide systematic errors into two categories: systematic errors of instrumental origin such as electronic pick up, and systematic errors arising from interactions of the neutron spin other than the $\sigma \cdot k$ interaction. The systematic errors of instrumental origin have been measured and shown to be negligible.

In the 1998 proposal and published technical papers [13, 15, 16, 18] we discuss the following errors from neutron spin interactions:

1. parity-allowed analyzing power in n–p elastic scattering,
2. circular polarization in γ-rays from $\vec{n} + p \rightarrow d + \gamma$,
3. parity-allowed asymmetry in $\vec{n} + p \rightarrow d + \gamma$,
4. beta decay of polarized neutrons,
5. PV asymmetry from ^{2}D impurities in the hydrogen target,
6. PV asymmetries from $\vec{n}+^6\text{Li} \rightarrow ^7\text{Li}^* \rightarrow \alpha + ^3\text{T}$,
7. Mott Schwinger scattering,
8. Stern Gerlach steering of the neutron beam,
9. neutron spin rotation, and
10. beta decay of polarized ^{28}Al from capture of polarized neutrons.

The apparatus was designed with the above sources of systematic error in mind, and in the 1998 proposal we show that the false asymmetries from each of them with our design is negligible compared to 1×10^{-8}.

Gamma-rays from polarized neutron capture on the aluminum windows of the spin flipper and cryostat are a potential source of systematic uncertainty that was not discussed in the 1998 proposal. We expect the aluminum γ-asymmetry to be small. We have measured this asymmetry at LANSCE to be zero with an upper limit of $|A_\gamma^{\text{Al}}| \leq 3 \times 10^{-7}$. The fraction of the $\vec{n} + p \rightarrow d + \gamma$ signal produced by neutron capture on Al is 0.05. This sets the upper limit for the false asymmetry in A_γ to 1.5×10^{-8}, which is small compared to the statistical uncertainty expected at LANSCE.

We have estimated the RMS γ-asymmetry from aluminum to be 4×10^{-8} using the statistical model of the compound nucleus, the measured spreading width of the hadronic weak interaction, and spectroscopic properties of aluminum. We therefore expect the systematic contribution at the SNS to be $< 2 \times 10^{-9}$. However, we will measure the Al asymmetry at the SNS and apply a correction, if necessary, to the runs with the para-hydrogen target. We estimate the time required to measure the aluminum γ-asymmetry to 7×10^{-8} so that the effect on the $\vec{n}+p \rightarrow d+\gamma$ uncertainty is negligible, to be 100 h at 1.4 MW.

The estimate of the size of systematic errors from some of the parity-conserving left-right asymmetries assumes that the γ-detector array is aligned with respect to the neutron polarization. The γ-detector array possesses a motion mechanism to align the detector with sufficient angular resolution to perform this alignment. Measurements at LANSCE to verify this alignment accuracy are in progress.

6 Beam Time Requirements

Neutrons of each wavelength, λ, provide a statistically independent determination of the γ-asymmetry. Adding the uncertanties in the determinations in quadrature gives the statistical weight and the uncertainty, σ_A, of the asymmetry:

$$\frac{1}{\sigma^2_{A_\gamma}} = \frac{1}{1+B_{\rm Al}} \frac{A_3 F_{\rm capture} T_{\rm mat} T_{\rm IC} G^2_\gamma \epsilon^2_{\rm SF}}{R^2_{\rm ns}} \int_{\lambda_1}^{\lambda_2} \frac{{\rm d}Y}{{\rm d}\lambda} T_{\rm n} P^2_{\rm n} {\rm d}\lambda,$$

where
$B_{\rm Al} = 0.05$, background from neutron capture on Al windows,
$A_3 = 64$ cm^2 is the beam cross section on the ^{3}He cell,
$F_{\rm capture} = 0.6$ is the fraction of neutrons that capture on hydrogen,
$T_{\rm mat} = 0.85 \times 0.96 = 0.82$ is the measured transmission through glass and Al windows,
$T_{\rm IC} = 0.95$ is the spectrum-weighted transmission through the aluminum and ^{3}He of one upstream ion chamber monitor,
$G_\gamma = 0.56$ is the effective analyzing power of the detector array for the $\sigma \cdot k$ correlation from a Monte Carlo calculation,
$\epsilon_{\rm SF}$=0.98 is the spin flip efficiency,
$R_{\rm ns} = 1.07$ is the ratio of the observed noise to counting statistics,
$\frac{{\rm d}Y}{{\rm d}\lambda}$ is the neutron flux from the guide at 1.4 MW given by figure 3,
$T_{\rm n}$ is the neutron transmission through a 6 atm cm thick polarized ^{3}He,
$P_{\rm n}$ is the neutron polarization, calculated using ^{3}He polarization of 55%,
$\lambda_1 = 2.34$ Å, and
$\lambda_2 = 5.63$ Å, see figure 4.

Assuming a flight path length of 20 m to the the hydrogen target, the uncertainty in A_γ for a 1 s long run is 3.8×10^{-5}. The time required to reach an uncertainty of 1×10^{-8} is then 4000 hours.

Based on these calculations for measurement of A_γ in the $\vec{n} + p \rightarrow d + \gamma$ reaction with a precision of 1×10^{-8} we plan to request
1) 7000 MWh (=5000 h $\times$ 1.4 MW) of beam for data collection and systematics studies and
2) 1000 h beam time at greater than 0.14 MW power for commissiong and tune up of the experiment.
7000 MWh of beam means that we will need 4000 h beam at 1.4 MW.

This statistical error estimate is based on the measured noise performance of the detector ($R_{\rm ns}$), Monte Carlo studies of the hydrogen target, the simulations of the FnPB flux, and the beam collimation which up to the ^{3}He spin filter is equal to A_3. Downstream of the spin filter the beam will expand and only a cleaning collimation will be used. The FnPB commissioning run will measure the neutron flux which will be used later to improve the statistical error estimate for the $\vec{n} + p \rightarrow d + \gamma$ experiment. The improvements to the ^{3}He neutron spin filter including higher polarization and larger cells would also improve the statistical error.

7 Schedule and costs

The plan of the $\vec{n} + p \to d + \gamma$ collaboration is to have the experiment ready on the FnPB for commissioning by the time the SNS reaches about 0.14 MW operation. The experiment therefore has the following major milestones:

1. Begin moving $\vec{n} + p \to d + \gamma$ experiment to SNS	Sep-06
2. SNS cold neutron beam line ready	Sep-07
3. Shielding in place and experiment assembled	Dec-07
4. Commissioning run complete	Mar-08
5. Start $\vec{n} + p \to d + \gamma$ production data	June-08

Costs for getting the experiment ready at the SNS will total about $380k. This rough cost estimate has no burden and does not include the cost of technical support. A breakdown of the estimate is:

Tasks	Cost ($k)
1. Disassembly and transportation to SNS	20
2. Shielding (EM and radiological)	160
3. Supports and stands	20
4. Air conditioning for 5 kW heat load	20
5. Hydrogen target infrastructure	130
6. Instrumentation/cabling	30

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