# Weak Interactions

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## Precision Measurements of Neutron Scattering Lengths using Neutron Interferometry

*with NIST, University of Missouri, Los Alamos, and UNC/Wilmington*

High precision measurements of neutron scattering lengths are of interest in the area of few-body physics. In the last few years there has been significant theoretical progress in performing accurate calculations of the properties of few-nucleon systems [1–3]. Nevertheless, calculations using realistic two-body NN potentials still underbind $^3$He and $^3$H. The n-d scattering length in the doublet S-wave channel is likewise poorly predicted by two-body NN force models. Convergence between theory and experiment for these important parameters of the 3N system is accomplished only by the addition of 3-nucleon forces. However, there are many possible forms for 3N forces and measurements of many two and three-nucleon observables are required to determine their form. In the case of the n+d system, this measurement yields the linear combination $b_{coh} = b_{1/2}/3 + 2b_{3/2}/3$ of the doublet and quartet n-d scattering lengths. The quartet S-wave scattering length $^4S_{3/2}$ can be unambiguously calculated. Because the three nucleons in this channel exist in a spin-symmetric state, and hence have an anti-symmetric space-isospin wave function, the scattering in this state is completely determined by the long-range part of the triplet S-wave NN interaction in the n-p channel; i.e. by n-p scattering and the properties of the deuteron.

With the neutron interferometer [4] at NIST, we have finished the analysis of measurements of the coherent scattering length in the n-p, and n-D systems. The results are: $b_{coh,H} = -3.738 \pm 0.002$ fm and $b_{coh,D} = 6.665 \pm 0.004$ fm. Both results are in agreement with the world averages of previous measurements, $b_{coh,H} = -3.741 \pm 0.002$ fm and $b_{coh,D} = 6.673 \pm 0.004$ fm. In the case of the n-D system we have compared the new world average, $b_{coh,D} = 6.668 \pm 0.003$ fm, to calculations of the coherent n-D scattering length using NN potentials with various 3-nucleon force additions chosen to fit the binding energy of the triton. Few theoretical calculations are in agreement with the data. The precision of the n-D coherent scattering length is now high enough that it needs to be taken into account as automatically as is the triton binding energy in determining possible contributions due to 3-nucleon forces. These results will be submitted soon to PRL and PRC.

A precision measurement of the coherent scattering length of $^3$He was also performed using the same techniques. Analysis of the data awaits only a correction from the virial coefficients of $^3$He gas. In combination with the very recent high-precision measurement of the difference of the scattering lengths of $^3$He at the ILL by Zimmer *et al.*, [5] this measurement will improve the knowledge of the n-$^3$He scattering lengths by an order of magnitude.

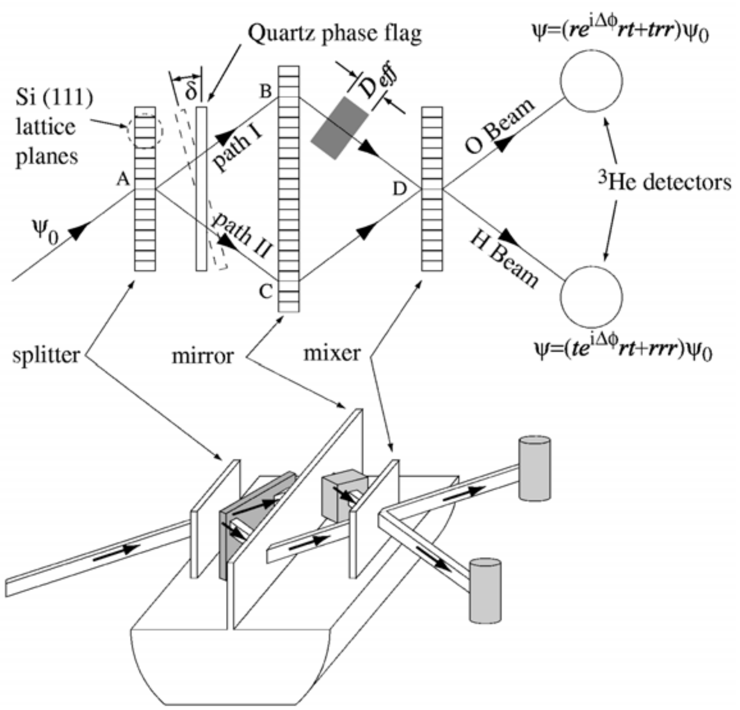

*Fig. 1: Top and side views of the NIST neutron interferometer. The neutron beam is split and recombined by diffraction from three blades of a monolithic silicon crystal. Insertion of matter into one of the beams gives a phase shift to the neutrons that is proportional to the coherent forward scattering amplitude.*

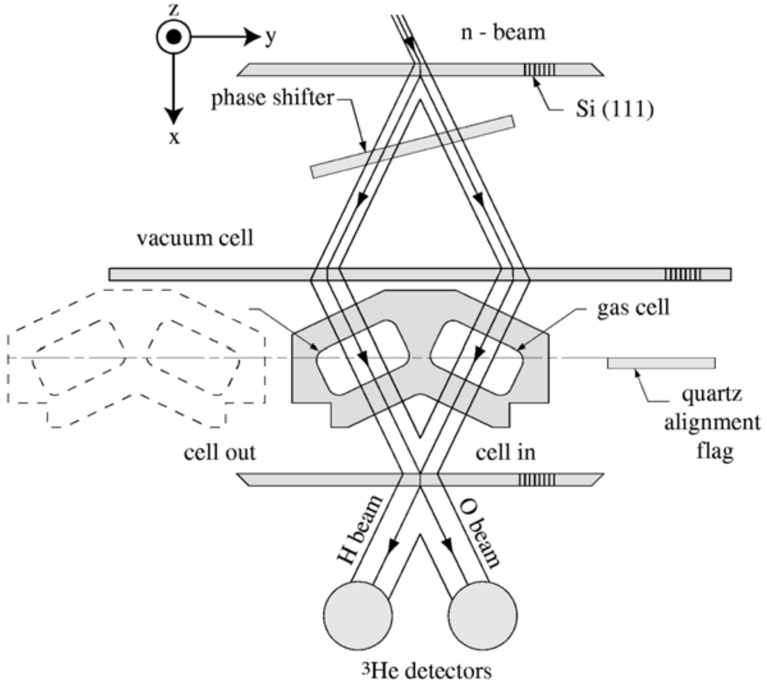

*Fig. 2: Top view of the NIST neutron interferometer showing the gas cell for the n-d scattering length measurement.*

## Parity Violation in Neutron Interactions in Simple Systems

*with LANL, the University of Michigan, the University of California at Berkeley, the University of New Hampshire, NIST, and KEK*

In the meson exchange picture of the weak {NN} interaction, weak pion exchange is particularly interesting since it should be dominated by neutral currents. This is the longest-range component of the weak {NN} interaction, and therefore presumably the most reliably calculable in its effects in the {NN} system. The exchange of neutral currents between quarks, however, has never been isolated experimentally in low energy processes. For all of these reasons, the coupling constant for weak π exchange, $h_\pi^1$, is of special interest.

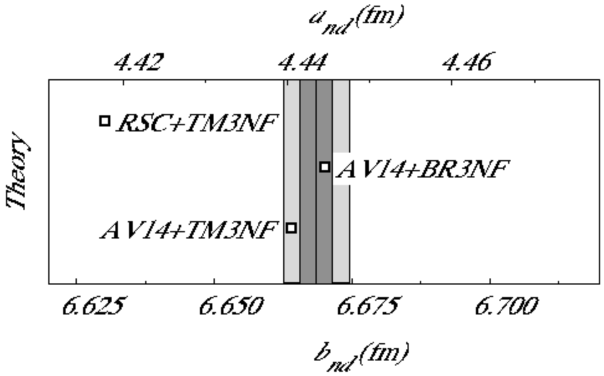

*Fig. 3: Comparison of the new world value of the coherent scattering length to various theories with 3-body forces fit to the triton binding energy. Of the several calculations available in the literature, there are the only ones that are close to experiment.*

The size of $h_\pi^1$ is not known. The most reliable estimate of the size of $h_\pi^1$ is believed to come from measurements of the circular polarization of 1081-keV γ-rays from the decay of $^{18}$F [6], which gives an upper limit of $h_\pi^1 \leq 1.3 \times 10^{-7}$. New information on $h_\pi^1$ may come from the recent observation of nuclear parity violation in the atomic parity violation experiment using $^{133}$Cs [7]. This experiment has detected for the first time the (parity violating) nuclear anapole moment.

A measurement in the nucleon-nucleon system sensitive to $h_\pi^1$ is needed to determine its value beyond a reasonable doubt. The system must be simple enough that calculations which can connect experimental observables to weak couplings can be performed reliably. In practice, this means that one must perform experiments in light nuclear systems, such as p, d, $^3$He, or $^4$He. Measurements of parity violation have been performed in p+p scattering and in p+$^4$He scattering. Nevertheless, neither measurement determines $h_\pi^1$. In the case of p+p parity violation, identical particle constraints forbid a contribution from weak charged pion exchange to first order, and weak neutral pion exchange is suppressed because it violates time reversal invariance (Barton's theorem). Therefore, p+p parity violation is quite insensitive to $h_\pi^1$. Parity violation in p+$^4$He scattering is sensitive in principle to $h_\pi^1$. However, it is also sensitive to other weak meson couplings, and so the observation does not isolate the value of $h_\pi^1$ uniquely.

The two measurements with low energy neutrons address the problem of determining $h_\pi^1$ in different ways. In low energy neutron reactions, the parity violating observables are primarily sensitive to both weak pion and rho exchange, which are the longest-range contributions (the identical particle constraint which suppresses weak pion exchange in p+p scattering does not apply to n+p). In the case of the n+p system, an analysis of the available low-energy channels shows that the reaction $n + p \rightarrow d + \gamma$ is almost entirely due to weak pion exchange. In particular, the relation between the PNC gamma ray asymmetry and $h_\pi^1$ is calculated to be $A_\gamma = -0.045\, h_\pi^1 + 0.001\, h_\rho^1 - 0.001\, h_\omega^1 - 0.002\, h_\rho'^1$ [8]. In the case of the n+$^4$He system, the parity violation is also dominated by weak pion and rho exchange, and one can combine a measurement with the existing measurement of parity violation in p+$^4$He to determine both. Calculations of the parity violating neutron spin rotation have been performed: the neutron spin rotation angle per meter is $\varphi = -0.97\, f_\pi - 0.32\, H_\rho^0 - 0.11\, H_\rho^1 - 0.22\, H_\omega^0 + 0.22\, H_\omega^1$ rad/m [9]. The calculations are expected to be reliable partly because the reaction involves only elastic scattering channels.

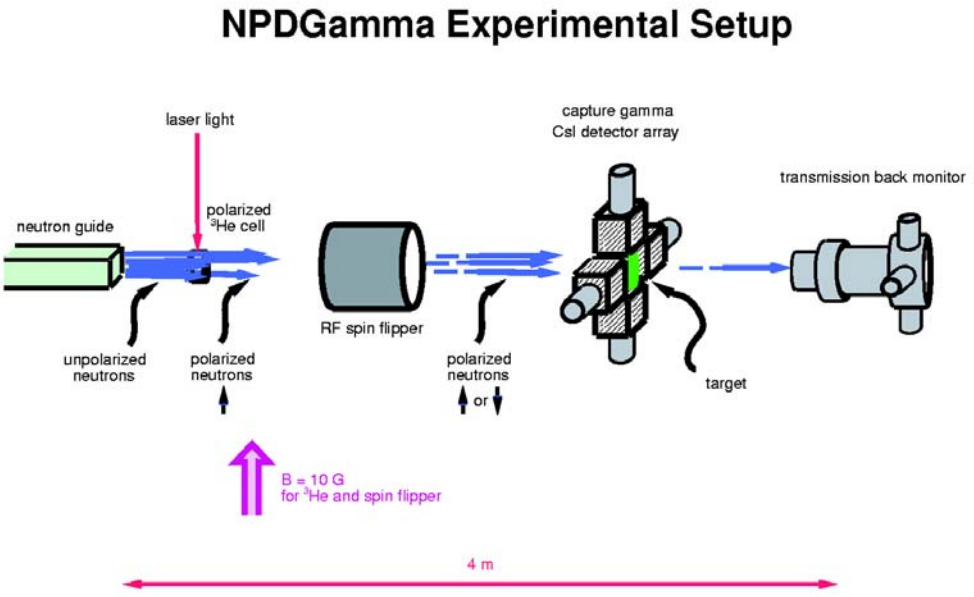

*Fig. 4: Diagram of the major components of the $n + p \rightarrow d + \gamma$ radiative capture parity violation experiment. IUCF is providing the liquid hydrogen target and the CsI detector array.*

The final result from the last experiment to search for the PV asymmetry in $\vec{n} + p \rightarrow d + \gamma$ was $A_\gamma = -1.5 \pm 4.7 \times 10^{-8}$ [10]. This result is in mild conflict with one of the $h_\pi^1$ estimates from the anapole moment measurement [11], but it is not sensitive enough to reach the range of values for $h_\pi^1$ predicted by theory. The limit reached in the first version of the neutron spin rotation experiment, $1.4 \times 10^{-6}$ rad/m, is also not sensitive enough to put an interesting constraint on $h_\pi^1$. We propose to measure $A_\gamma$ to a precision of $\pm 5 \times 10^{-9}$ [12], which will determine $h_\pi^1$ to $\pm 4 \times 10^{-8}$, and to measure $\Phi$ to a precision of $\pm 3 \times 10^{-7}$, which should be sensitive enough to see a nonzero effect. A diagram of the apparatus is shown in Fig. 4. At a minimum, such results will clearly distinguish between the $^{18}$F and $^{133}$Cs values for $h_\pi^1$. In addition, there is also a strong possibility that a non-zero result will be seen in one of the experiments and that the value of $h_\pi^1$ will finally be known.

To measure the parity-violating gamma asymmetry in the $\vec{n} + p \rightarrow d + \gamma$ experiment, transversely polarized neutrons are absorbed in a liquid hydrogen target and the $\gamma$-rays are detected in current mode by a segmented cylindrical CsI array surrounding the target. The parity violating signal consists of an up-down asymmetry in the $\gamma$ intensity correlated with the neutron polarization direction: $d\sigma/d\Omega = (1 + A_\gamma \cos\theta)/4\pi$, where $\theta$ is the angle between the gamma direction and the neutron polarization. The basic experimental strategy is to isolate this contribution by flipping the neutron spin and looking for a correlated asymmetry in the signal from the gamma detector array. Figure 5 shows the conceptual design of the experiment.

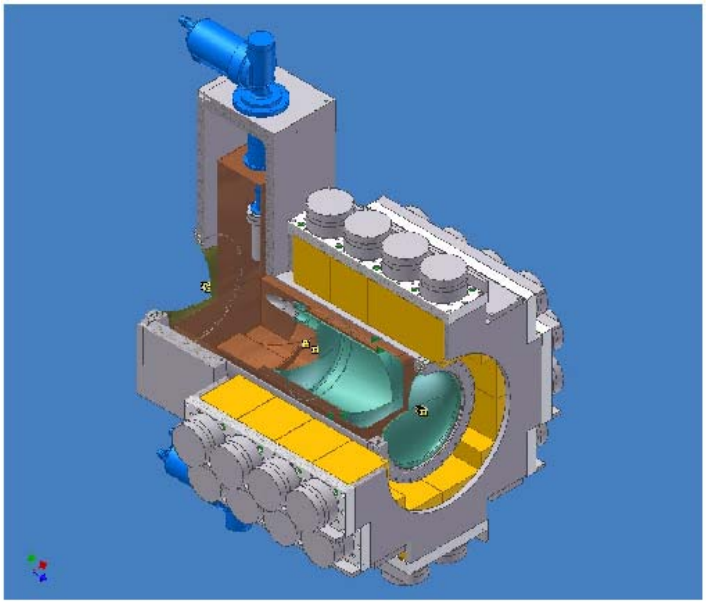

*Fig. 5: Design of the CsI array and the $LH_2$ target.*

The experiment is in the construction phase. Indiana is responsible for the design and construction of the CsI detector array and the liquid hydrogen target. The design of the CsI array is complete and construction is in progress. 48 CsI detectors, purchased with funds from a MRI awarded by NSF in fall 2001, have been successfully tested and shipped to Los Alamos. Graduate student Mike Gericke has moved to Los Alamos to assemble and test the array. Light output from the detectors averages above 1000 photoelectrons per MeV, an order of magnitude greater than required in the experiment. Assembly of the array will occur at Los Alamos in fall 2002.

The design of the $LH_2$ target is complete and subsystems are under construction. One of the CsI detectors is shown in Fig. 6. The target chamber shown in Fig. 7 is being manufactured from titanium. The $LH_2$ target is slated for shipment to Los Alamos in early 2003.

*Fig. 6: Picture of one of the 48 CsI detectors for the NPDG experiment. The elements of the array are now at Los Alamos for final assembly.*

*Fig. 7: Picture of the downstream portion of the titanium liquid hydrogen target vessel.*

## Neutron Spin Rotation in $^4$He

*with the University of Washington, North Carolina State, and NIST*

Indiana is collaborating in a second-generation experiment to search or the parity-violating rotation of a transversely polarized neutron beam as it passes through a target of liquid helium. This measurement is somewhat analogous to the phenomenon of optical dichorism in light optics, in which the plane of polarization of a light beam is rotated as it passes through an "optically active" substance (in practice a substance, like sugar, in which the molecules have a chiral structure). In the case of the neutrons, however, the chirality is present not in the internal structure of the target but in the weak interaction, which violates parity.

The experimental apparatus is analogous to a light optics experiment with crossed polarizers and analyzers. If there is no spin rotation, the experimental signal should be zero. A small spin rotation will lead to an asymmetry in the counting rates for the neutron spin analyzer in its two possible states. We will be looking for a spin rotation angle on the order of a microradian.

Indiana has accepted responsibility for designing a new superfluid $^4$He target chamber for the experiment. This project is the Ph.D. thesis for Chris Bass and Da Luo. The target chamber has been designed and is under construction. The cryostat was moved from NIST to Indiana in the summer of 2001 and the magnetic shielding in the summer of 2002. We anticipate reducing the systematic effects due to stray magnetic fields by an order of magnitude by using more magnetic shielding. Already using a third magnetic shield made of Cryoperm we have reduced the magnetic field in the target region to the 50 $\mu$Gauss level without active compensation at room temperature. Based on the systematic effects observed in the previous version of the experiment, this should allow the experiment to see an unambiguous parity violation signal.

## Polarized $^3$He

*with NIST*

Precision measurements of neutron decay parameters such as the decay rate and angular correlation coefficients of the decay products are of fundamental importance. In combination with a separate measurement of the neutron decay rate, for example, a measurement of the electron asymmetry coefficient in polarized neutron decay (the $A$ coefficient) can be used to determine the weak polar vector-axial vector coupling ratio $\lambda = g_A/g_V$ and, by comparison with muon decay, the CKM matrix element $V_{ud}$, one of the parameters of the Standard Model of elementary particle interactions. The unitarity of the CKM matrix is dominated by the accuracy of the large diagonal elements $V_{ud}$, $V_{cs}$, and $V_{tb}$. Study of neutron beta decay offers the best opportunity to probe the unitarity of the CKM matrix. While it is difficult to measure $V_{ud}$ to 0.1%, there is no hope of measuring $V_{cs}$ or $V_{tb}$ to this accuracy in the foreseeable future. Also, measurements of the neutrino asymmetry $B$ in polarized neutron decay can be used to place interesting constraints on possible deviations from the Standard Model in the charged current sector of the weak interactions, such as the possible existence of right-handed weak currents. It is therefore important to improve the accuracy of these measurements.

The measurement of absolute neutron beam polarization is now a serious limitation on the accuracy with which neutron beta decay asymmetry measurements can be performed [13]. We have conducted an accurate absolute measurement of the polarization of a neutron beam polarized using transmission through polarized $^3$He gas. We have achieved an absolute accuracy of ±0.3%, better than previous measurements in this energy range by almost a factor of 5, and we believe that a further order of magnitude improvement is possible. These results have recently been published [14].

## Neutron Lifetime

*with NIST*

The decay rate of the neutron is an important parameter in low energy weak interactions. In combination with other neutron decay measurements, it can be simply related to one of the parameters of the Standard Model of elementary particle interactions: the CKM matrix element $V_{ud}$ (formerly known as the Cabibbo angle). In the Standard Model, the KM matrix transforms the mass eigenstate basis into the weak interaction eigenstate basis. If the model is correct this matrix must be unitary. A deviation from KM matrix unitarity, if established, would be indirect evidence for physics beyond the Standard Model.

Precision measurements of neutron decay parameters offer the best hope for improving the accuracy of $V_{ud}$. $V_{ud}$ has traditionally been determined from measurements of $0^+ \rightarrow 0^+$ transitions in nuclei. The accuracy of the value for $V_{ud}$ derived from these measurements, while higher than that from the neutron measurements at present, is limited by theoretical uncertainties in nuclear structure corrections to the decay rates. The current values for $V_{ud}$ derived from nuclear decays ($0.9734 \pm 0.0007$) and neutron decay ($0.9810 \pm 0.0021$) are in serious disagreement. In addition, the neutron result causes a $3\sigma$ deviation from KM matrix unitarity [15].

The neutron lifetime also influences the predictions of the theory of Big Bang Nucleosynthesis (BBN) for the primordial helium abundance in the universe and the number of different types of light neutrinos $N_\nu$ (and therefore the number of generations) in the Standard Model. About 90% of the uncertainty in the BBN prediction for the primordial helium abundance comes from the accuracy of the neutron decay rate [16]. Improved neutron decay rate measurements are therefore important for sharpening the BBN prediction.

The experiment at the NIST Cold Neutron Research Facility to measure the decay rate of the neutron has been completed. The measurement was performed by confining the protons from in-beam neutron decays in a Penning trap and counting the trapped protons while simultaneously monitoring the neutron flux passing through the trap. The value of the neutron lifetime was determined to be $\tau_{\mathrm{n}} = 884.6 \pm 4.0$ seconds.

The error can be reduced to the 1-second level with an absolute neutron flux measurement. A monochromatic neutron beam at NIST (designated NG6M) has been reconstructed and commissioned by Indiana and NIST for performing absolute neutron flux measurements. The Indiana-designed neutron radiometer was installed and operated successfully using a $^6$LiMg target and was able to measure the absolute neutron flux at the 0.1% level of absolute accuracy. This measurement formed the Ph.D. thesis of Zema Chowdhuri (now postdoc/instrument scientist at Maryland/NIST). This measurement will be checked by an independent measurement using a liquid $^3$He target (Greg Hansen's thesis project). The absolute value of the wavelength of the monochromatic beam, which had to be remeasured after the beam was reconstructed, has recently been completed. Measurements of the absolute neutron flux using liquid $^3$He will start in fall 2002.

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