

Precision Measurement of the n - ^3He Incoherent Scattering Length Using Neutron Interferometry

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We report the first measurement of the low-energy neutron- ^3He incoherent scattering length using neutron interferometry: $b'_i = (-2.512 \pm 0.012 \text{ stat} \pm 0.014 \text{ syst}) \text{ fm}$. This is in good agreement with a recent calculation using the AV18 + $3N$ potential. The neutron- ^3He scattering lengths are important for testing and developing nuclear potential models that include three-nucleon forces, effective field theories for few-body nuclear systems, and neutron scattering measurements of quantum excitations in liquid helium. This work demonstrates the first use of a polarized nuclear target in a neutron interferometer.

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Recent years have seen remarkable advances in the decades-long struggle to compute nuclear structure and low-energy observables from the nucleon-nucleon (NN) potential. Modern NN potentials such as AV18 [1], CD-Bonn [2], and the Nijmegen potentials [3] produce good fits to experimental NN scattering observables up to 350 MeV. Quantum Monte Carlo methods which include three-nucleon ($3N$) potentials such as Urbana IX [4] precisely reproduce the level spectra of light nuclei up to $A = 12$ [5–7]. Effective field theory methods, which are logically related to the QCD Lagrangian and allow for better estimates of theoretical uncertainty, show promise for similar success in the near future [8]. But even with the inclusion of many-body forces, modern NN potentials have had only modest success in predicting scattering observables in light nuclei. The aim of our program is to contribute to a complete set of basic experimental results for light nuclei which can be used in formulating the next generation of NN and many-body potentials.

Neutron scattering lengths at the zero-energy limit can be directly and accurately measured using neutron interferometry. These are excellent high-precision benchmarks for testing and/or calibrating the latest few-nucleon theoretical methods. Recent precision scattering length measurements include n -H, n -D, and n - ^3He (coherent) [9–12]. In general, the agreement between these data and the best theoretical models, including $3N$ forces, is not very good. The situation with ^3He is further clouded by the fact that two recent precision determinations of the coherent scattering length disagree by more than 7 standard deviations [11,12]. The incoherent scattering length was recently measured from the pseudomagnetic neutron spin rotation in polarized ^3He gas [13]. Here we report on the first direct measurement of the n - ^3He incoherent scattering length using neutron interferometry. This is also the first successful use of a polarized nuclear target in a neutron inter-

ferometer. The incoherent scattering length is also important for interpreting experimental studies of the scattering law $S(Q, \omega)$ of liquid ^3He , as pointed out in Ref. [13].

A neutron interferometer [14–16] splits the matter wave of a single neutron into two coherent paths and then recombines them using Bragg diffraction perfect single-crystal silicon. A target placed in one beam path of the neutron interferometer produces a phase shift $\phi = -N_3 \lambda b' z$, where N_3 and z are the nuclear density and length of the target, respectively (^3He in this case), λ is the neutron de Broglie wavelength, and b' is the real part of the bound neutron scattering length of the target atom. The bound scattering length is appropriate because there is no momentum transfer between the neutron and target. It is related to the free atom scattering length by $a = bA/(A + 1)$, with A the atom/neutron mass ratio. In general, the interaction amplitude is complex and spin-dependent so the scattering length depends on the nuclear spin I and neutron spin σ_n :

$$b = b' + ib'' = b_c + \frac{2b_i}{\sqrt{I(I+1)}} \mathbf{I} \cdot \boldsymbol{\sigma}_n, \quad (1)$$

with the coherent (b_c) and incoherent (b_i) scattering lengths defined by

$$b_c = \frac{I+1}{2I+1} b_+ + \frac{I}{2I+1} b_-, \quad (2)$$

$$b_i = \frac{\sqrt{I(I+1)}}{2I+1} (b_+ - b_-), \quad (3)$$

and b_+ and b_- correspond to total spin channels $I + \frac{1}{2}$ and $I - \frac{1}{2}$, respectively. If two phase shift measurements are made, ϕ^\uparrow where $\boldsymbol{\sigma}_n$ and P_3 (the ^3He polarization) are parallel and ϕ^\downarrow where $\boldsymbol{\sigma}_n$ is reversed by a neutron spin flipper, with $\Delta\phi = \phi^\uparrow - \phi^\downarrow$, we have

$$\Delta b' = b'_+ - b'_- = -\frac{2\Delta\phi}{N_3\lambda z P_3}. \quad (4)$$

The experiment was performed at the NIST Center for Neutron Research's Neutron Interferometry and Optics Facility [17]. Figure 1 shows the basic scheme. A 0.235 nm wavelength neutron beam was extracted and focused by two pyrolytic graphite monochromators. A graphite beam filter reduced contamination from higher order Bragg reflections (to $<10^{-3}$). The beam then passed through a transmission-mode supermirror in which one spin state was preferentially reflected and absorbed and the other transmitted, producing 93% neutron polarization. Following the polarizer was a spin flipper that rotated the neutron spin by 180° by Larmor precession when energized. A pair of 56-cm-diameter Helmholtz coils produced a holding field of 1.48 mT centered on the ^3He cell. The perfect crystal silicon interferometer was the skew-symmetric type with (220) reflecting planes. The initial (no target) fringe contrast was 85%.

A novel feature of this experiment was the use of a polarized gas target in the neutron interferometer. The desired precision and the space available inside the interferometer called for a small target cell with uniform length and high polarization. Space constraints as well as the need to avoid thermal gradients near the interferometer precluded polarizing the cell *in situ*. Therefore we required a cell with a long spin-relaxation time so it could be polarized outside the apparatus, transported and positioned in the interferometer, and remain polarized in place for several days of measurement. We used the spin-exchange optical pumping method (see, e.g., [18,19]) to polarize the target. Two different target cells, with *in situ* spin-relaxation times of 115 and 35 h, were used in the experiment. The intrinsic relaxation time of the longer-lived cell was measured to be 370 h [20]. The cells were cylindrical with optically sealed 4-mm-thick flat windows, fabricated from boron-free aluminosilicate glass [21]. The outside dimensions were 42 mm in length and 25 mm in diameter. Each cell was filled to a ^3He pressure of approximately

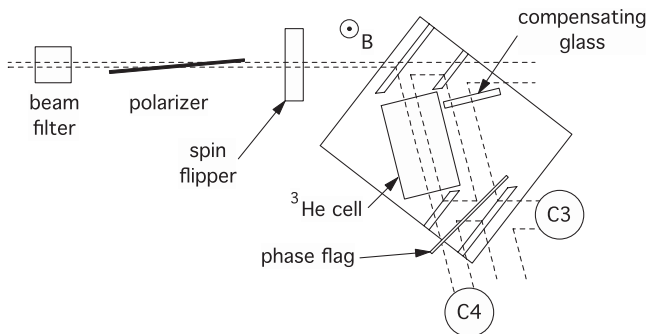


FIG. 1. Schematic representation of the experiment (not to scale). The dashed lines indicate the neutron beam paths. The interferometer crystal was fabricated by the Physics Machine Shop at the University of Missouri, Columbia; a photo can be found in Ref. [25].

180 kPa (1.8 bar), chosen to roughly minimize the statistical uncertainty. When a maximum ^3He polarization of about 65% was obtained in the polarization setup, the cell was moved to the neutron interferometer.

The data were collected in scans that lasted 4–9 h each. For each scan the phase flag angle ϵ —relative to the plane of the interferometer blades—was moved over a small range in steps of 2.18 mrad. At each phase flag position, the spin flipper was modulated in an off-on-on-off sequence, and the count rate in the *O*-beam detector (C3 in Fig. 1) was recorded. A typical scan is shown in Fig. 2. The count rate for each spin flipper state was fit to

$$I(\epsilon) = c_0 + c_1 \cos[c_2 f(\epsilon) + \phi], \quad (5)$$

where c_0 , c_1 , c_2 , and ϕ are fit parameters and

$$f(\epsilon) = \frac{\sin\theta_B \sin\epsilon}{\cos^2\theta_B - \sin^2\epsilon} \quad (6)$$

is the geometrical factor for the phase flag, with θ_B the Bragg angle of the interferometer. The difference in the extracted ϕ for the two fits is $\Delta\phi = (\phi^\uparrow - \phi^\downarrow)$. Typically, the reduced χ^2 for these fits were between 0.8 and 1.3. Poor quality scans, in which the reduced $\chi^2 > 1.5$, were discarded. Most of the poor scans were due to phase instability immediately following a cell transfer, which caused temperature and mechanical fluctuations that persisted for several hours.

The product $N_3\lambda z P_3$ needed in Eq. (4) was measured continuously during the experiment. The first three factors were constant, but P_3 decreased exponentially with time as the cell polarization relaxed. The stronger absorption for one neutron spin state causes an asymmetry A_4 that depends on P_3 , between the count rates N^\uparrow and N^\downarrow measured in detector C4 (see Fig. 1):

$$A_4 = \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} = \frac{\frac{1}{2}(1+s)P_n \tanh\xi}{1 + \frac{1}{2}(1-s)P_n \tanh\xi}, \quad (7)$$

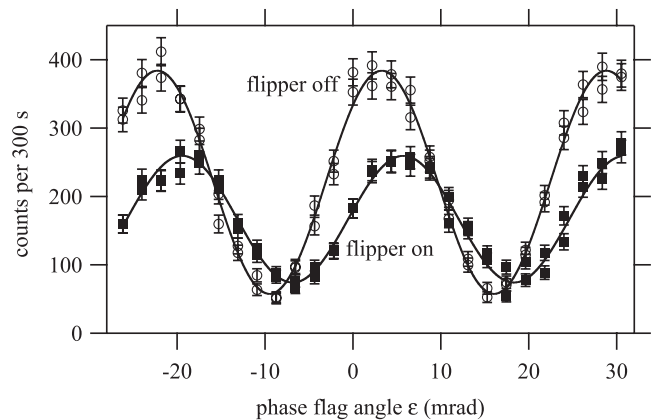


FIG. 2. A typical phase scan, showing counts in the *O*-beam detector (C3) for neutron spin parallel (open circles) and anti-parallel (solid squares) to the ^3He polarization and their best fits to Eq. (5).

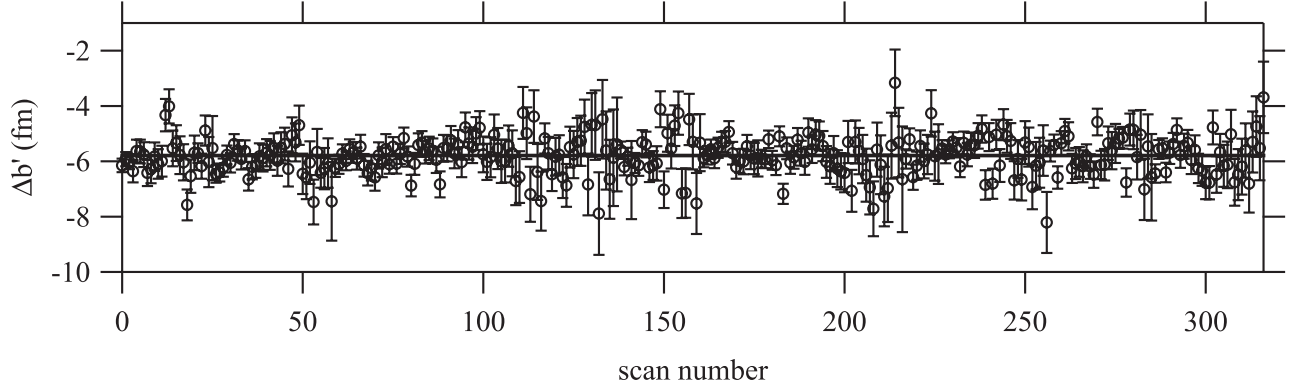


FIG. 3. $\Delta b'$ for 317 scans. Error bars shown are counting statistics only. The weighted average is $(-5.795 \pm .028)$ fm with reduced $\chi^2 = 371/316$.

with

$$\xi = \left(\frac{\sigma_0 - \sigma_1}{4\lambda_{\text{th}}} \right) N_3 \lambda z P_3, \quad (8)$$

where σ_0 (σ_1) is the ^3He thermal neutron absorption cross section for the singlet (triplet) channel and λ_{th} is the reference thermal neutron wavelength (0.1798 nm). The total thermal absorption cross section $\sigma_{\text{th}} = \frac{1}{4}\sigma_0 + \frac{3}{4}\sigma_1 = 5333(7)$ b [22] is dominated by σ_0 due to the strong singlet resonance at -0.5 MeV, but the triplet cross section is not well known [23]. In the literature it has often been assumed that $\sigma_1 = 0$, but as pointed out in Ref. [13] that assumption is not justified. Hofmann and Hale recently calculated the imaginary triplet scattering length a_1'' using the R matrix and AV18 with $3N$ forces and obtained -0.001 and -0.005 fm, respectively [24]. In the same paper, they show that AV18 + $3N$ underpredicts a_0'' by as much as 30% compared to the experimental value. Therefore to be conservative we use $a_1'' = (-0.005 \pm 0.005)$ fm; this range includes the R -matrix value and allows for an underestimate by a factor of 2 by AV18 + $3N$. With $\sigma_1/\sigma_0 = a_1''/a_0''$ we have $\sigma_0 - \sigma_1 = (21\,236 \pm 28 \text{ experimental} \pm 100 \text{ theoretical})$ b. The average value of A_4 for one scan was used to extract $N_3 \lambda z P_3$ for that scan. Studies using simulated data verified that the systematic error due to using the average value of A_4 was negligible.

Because the neutron polarization is not 100%, the interferogram [Eq. (5)] is actually a sum of two interferograms, one for each neutron spin state, with relative intensities given by the ratio of neutron spin states at the exit of the ^3He cell. We apply a correction to the phase difference between the two spin flipper states:

$$\Delta\phi_{\text{meas}} = \arctan\left(\frac{\sin\Delta\phi}{\eta^\uparrow + \cos\Delta\phi}\right) - \arctan\left(\frac{\eta^\uparrow \sin\Delta\phi}{1 + \eta^\uparrow \cos\Delta\phi}\right). \quad (9)$$

Here $\Delta\phi_{\text{meas}}$ is the measured phase difference, $\Delta\phi$ is the phase difference one would obtain with 100% neutron

polarization, and η^\uparrow (η^\downarrow) is the ratio of minority to majority neutron spin states at the exit of the cell with the spin flipper off (on), given by

$$\eta^\uparrow = \left(\frac{1 - P_n}{1 + P_n} \right) e^{-2\xi}, \quad (10)$$

$$\eta^\downarrow = \left(\frac{1 - sP_n}{1 + sP_n} \right) e^{+2\xi}. \quad (11)$$

P_n is the neutron polarization, and s accounts for the slight decrease in polarization with the spin flipper energized; i.e., $P_n \equiv P_n^\uparrow$ and $s = P_n^\downarrow/P_n^\uparrow$.

The neutron polarization at the interferometer entrance, for both spin flipper states, was determined 16 times during the six month duration of the experiment by replacing the interferometer crystal with an optically thick ($N_3\sigma z \approx 3$) polarized ^3He analyzer cell. We obtained $P_n = 0.9291 \pm 0.0008$ and $s = 0.9951 \pm 0.0003$. This was stable over the course of the experiment.

A potential systematic error can arise because the magnetic field in the interferometer is not perfectly uniform. A field gradient will cause a phase difference between the two neutron paths that reverses sign, so does not cancel, when the spin flipper is energized. The size of this effect was determined in three ways: (i) direct measurement by repeating the experiment with the cell removed,

TABLE I. Uncertainty budget for $\Delta b'$. All uncertainties quoted in this Letter are one sigma.

Source	Uncertainty (fm)
Phase instability	0.013
Neutron polarization P_n	0.006
Neutron spin flip factor s	0.002
Magnetic field gradient	0.009
n - ^3He thermal abs. cross section σ_{th}	0.008
n - ^3He triplet abs. cross section σ_1	0.027
Combined systematic uncertainty	0.033
Counting statistics	0.028

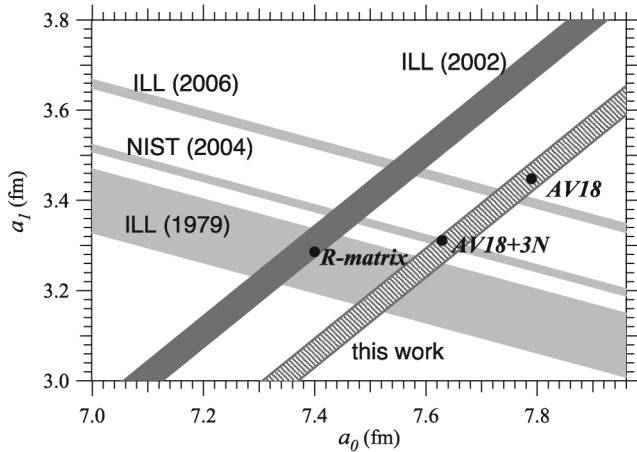


FIG. 4. Summary of the triplet and singlet n - ${}^3\text{He}$ free neutron scattering lengths (real parts). The three coherent (unpolarized) measurements labeled ILL (1979) [26], NIST (2004) [11], and ILL (2006) [12] used neutron interferometry. The incoherent (polarized) measurement ILL (2002) [13] used pseudomagnetic spin rotation. The three theoretical points shown are from Ref. [24].

(ii) extrapolation of the data to $P_3 = 0$, and (iii) an estimate of the gradient from the observed relaxation time of P_3 . The first two methods were consistent with zero. The third indicated a small effect with an associated correction to $\Delta b'$ of 0.009 fm. Since we do not know the sign, we take this to be the systematic uncertainty due to the magnetic field gradient and make no correction.

For each scan we numerically inverted Eq. (9) to extract $\Delta\phi$ from $\Delta\phi_{\text{meas}}$ and then divided by $N_3\lambda z P_3/2$ to obtain a value for $\Delta b'$ [see Eq. (4)]. Figure 3 shows $\Delta b'$ for 317 scans from 12 weeks of measurements. The weighted average is (-5.795 ± 0.028) fm with reduced $\chi^2 = 371/316$. The low probability of this fit (about 2%) indicates a small amount of phase instability, mainly due to temperature fluctuations, that is typical for this instrument. Because the instability is quasirandom, we add in quadrature an additional uncertainty of 0.20 fm to each scan in order to obtain reduced $\chi^2 = 1$. The new weighted average is (-5.802 ± 0.031) fm; hence, we obtain

$$\Delta b' = (-5.802 \pm 0.028 \text{ stat} \pm 0.033 \text{ syst}) \text{ fm} \quad (12)$$

using the combined systematic uncertainty from Table I. With Eq. (3) we can express this result as the real part of the incoherent scattering length: $b'_i = (-2.512 \pm 0.012 \text{ stat} \pm 0.014 \text{ syst})$ fm. In terms of the free scattering length it is $a'_1 - a'_0 = (-4.346 \pm 0.021 \text{ stat} \pm 0.025 \text{ syst})$ fm. The poorly known ratio σ_1/σ_0 contributes the largest systematic uncertainty to both this experiment and Ref. [13]. It may be improved in the future, so it is useful to express our result with this quantity factored out: $b'_i = [-2.515(1 - \sigma_1/\sigma_0) \pm 0.012 \text{ stat} \pm 0.008 \text{ syst}]$ fm. Figure 4 shows a summary of a_0 and a_1 in the n - ${}^3\text{He}$ system from the most recent coherent and incoherent scattering length measurements. Our result is in good agree-

ment with the calculation by Hoffman and Hale using the AV18 + $3N$ potential [24] but disagrees with the only previous measurement of this quantity by Zimmer *et al.*, $b'_i = (-2.365 \pm 0.020)$ fm [13], which used a very different technique, pseudomagnetic spin rotation. The disagreement between the various experiments remains a problem that must be resolved by future work.

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