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Upper bound on parity-violating neutron spin rotation in ^{4}He

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We report an upper bound on parity-violating neutron spin rotation in ^{4}He. This experiment is the most sensitive search for neutron-weak optical activity yet performed and represents a significant advance in precision in comparison to past measurements in heavy nuclei. The experiment was performed at the NG-6 slow-neutron beamline at the National Institute of Standards and Technology (NIST) Center for Neutron Research. Our result for the neutron spin rotation angle per unit length in ^{4}He is $d\phi/dz = [+1.7 \pm 9.1(\text{stat.}) \pm 1.4(\text{sys.})] \times 10^{-7}$ rad/m. The statistical uncertainty is smaller than current estimates of the range of possible values of $d\phi/dz$ in n+^{4}He.

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Introduction and theoretical overview. We report an upper bound on the parity-violating neutron spin rotation angle per unit length, $d\phi/dz$, in ^{4}He. The phenomenon of neutron spin rotation can be understood in terms of neutron optics. The parity-violating (PV) weak interaction between the neutrons and the medium causes the amplitudes of the positive and negative neutron helicity states of polarized neutrons to accumulate different phases. The difference ϕ_{PV} between the phase shifts of the helicity states leads to a rotation of the neutron polarization vector about its momentum, which manifestly violates parity [1]. The rotation angle per unit length of a neutron of wave vector k in a medium of density ρ is $d\phi/dz = 4\pi\rho f_{\text{PV}}/k$, where f_{PV} is the forward limit of the parity-odd p-wave scattering amplitude. Because f_{PV} is proportional to the parity-odd correlation $\vec{\sigma}_n \cdot \vec{k}_n$ with $\vec{\sigma}_n$ the neutron spin vector and $\vec{k}_n$ the neutron momentum, $d\phi/dz$ is constant as $k \to 0$ in the absence of resonances [2].

Neutron spin rotation is expected from quark-quark weak interactions in the Standard Model, which induce weak interactions between nucleons that violate parity. Because the energies involved in our measurement are well below the energy scale Λ_{QCD} where quantum chromodynamics (QCD) becomes a strongly- interacting theory, the nucleon-nucleon (NN) weak interaction involves the unsolved nonperturbative limit of QCD and therefore remains one of the poorly understood sectors of electroweak theory. Parity-odd neutron spin rotation has been measured in heavy nuclei [3–5], but the dynamics are too complicated to use this information to learn about the NN weak-interaction amplitudes. To do this one must measure parity-odd neutron spin rotation and other parity-odd observables in light nuclei such as H, D, ^{3}He, and ^{4}He. Because strong-interaction effects are now calculable [6] in few-body nuclei and weak amplitudes can be added as a perturbation, several new calculations of parity-odd effects in these systems have appeared recently [7–13] to complement earlier works [14–16]. The expected size of the parity-odd rotation angle in such few-body systems is about 10^{-6} to 10^{-7} rad/m [17], and our measurement has achieved a precision in this regime.

NN weak-interaction amplitudes are important for several reasons. Because the range for W and Z exchange between quarks is small compared to the nucleon size, NN weak-interaction amplitudes are one of the few observables which are first-order sensitive to quark-quark correlations in the nucleon. At energies well below the electroweak scale, the quark-quark weak interaction can be written in a current-current form with pieces that transform under isospin as $\Delta I = 0, 1, 2$. The most sensitive experiments designed to search for the $\Delta I = 1$ NN weak channel in the ^{18}F nucleus do not reveal any effect [18]. Coupled with theoretical arguments [19] made in the context of a meson exchange model of the NN weak interaction it seems [14,16] that the $\Delta I = 1$ NN weak amplitude is smaller than expected. A similar scientific puzzle has existed for a long time in the strangeness-changing nonleptonic weak decays of hadrons. Both nonleptonic weak-kaon decays (which have been known for decades to be greatly amplified in the $\Delta I = 1/2$ channel) and nonleptonic weak decays of hyperons exhibit patterns whose dynamical source is still not fully understood [20]. If these unexpected patterns in the isospin dependence of nonleptonic weak amplitudes are confirmed by measurements in the NN and few-nucleon systems, it would

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indicate that this dynamical puzzle operates for all light quarks (rather than just the strange quark) and is therefore a nontrivial QCD dynamical phenomenon of general interest [8]. The NN weak interaction is also thought to be one of the few systems sensitive to quark-quark neutral-current effects at low energy, because at the quark level one expects the charged current contribution to $\Delta I = 1$ NN weak amplitudes to be suppressed by $V_{us}^2/V_{ud}^2 = 0.1$ relative to neutral currents. Lattice gauge theory [21] can be used to calculate the long-range component of the $\Delta I = 1$ NN weak interaction. Quark-quark and NN weak interactions also induce parity-odd effects in electron scattering [22,23], nuclear decays [15], compound nuclear resonances [24,25], and atomic structure, where they are the microscopic source for nuclear anapole moments [26–29]. The comparison between NN weak amplitudes in few-nucleon systems and heavy nuclei can also offer theoretical insight into the relative importance of possible heavy Majorana particle exchange in neutrinoless double β decay [30].

Of the five independent weak transition amplitudes present in NN elastic scattering at low energy [31], only the ${}^1S_0$-${}^3P_0$ proton-proton amplitude is fixed from experiment [32–35]; the rest are unknown. The existing calculation of $d\phi/dz$ in n-^{4}He ($d\phi/dz = -0.97 f_\pi - 0.22h_\omega^0 + 0.22h_\omega^1 - 0.32h_\rho^0 + 0.11h_\rho^1$) [36] was conducted within the meson exchange picture developed by Desplanques, Donoghue, and Holstein (DDH) [14], which uses π, ρ, and ω exchange parametrized by weak couplings at the NN vertex labeled by superscripts which indicate the isospin change. Within the DDH approach $d\phi/dz$ in n-^{4}He spans a range of $\pm 1.5 \times 10^{-6}$ rad/m this broad range of possibilities is dominated by the uncertainties in the weak couplings and reflects in part our poor understanding of quark-quark correlation physics in QCD.

Experimental technique and measurement. The experimental technique has been presented in [37,38] and only an overview is given here. The apparatus shown in Fig. 1 must distinguish small PV rotations from rotations that arise from magnetic fields. $\phi_{\rm PV}$ is isolated by alternately moving the medium in front of and behind a neutron spin precession coil and measuring the change in the spin rotation angle using the neutron equivalent of a crossed polarizer-analyzer pair familiar from light optics. Neutrons polarized along $\hat{y}$ enter a central precession coil with an internal magnetic field along $\hat{y}$ (π-coil), which precesses a spin component along $+\hat{x}$ to $-\hat{x}$. The contribution to the total rotation angle coming from parity violation in the liquid changes sign as the liquid is moved. To further suppress systematic uncertainties and noise, the beam and apparatus are split into right and left halves, and the targets are filled so that the liquid occupies the chamber downstream of the π-coil on one side and the chamber upstream of the π-coil on the other side. The PV components of the neutron spin rotation angle have opposite signs on each side, and the difference of the two rotation angles is insensitive to both static residual magnetic fields and any common-mode time-dependent magnetic field integrals along the neutron trajectories.

The experiment was performed at the NG-6 slow neutron beamline at the National Institute of Standards and Technology (NIST) Center for Neutron Research [39]. The neutrons were polarized vertically by a polarizing supermirror [40] and enter the magnetic shield-target region using a glass neutron guide and a magnetic field from an input coil to transport and preserve the neutron polarization [41]. The target vessel is mounted inside a magnetic shield that is centered in a nonmagnetic liquid helium cryostat supported in turn inside two more layers of magnetic shielding. The liquid is moved between the four separate target chambers using a centrifugal pump immersed in a 4 K liquid helium bath outside the target with flexible tubes pulled by strings to determine which pair of target chambers fill or drain [37]. Internal fluxgate magnetometers indicate a typical internal axial magnetic field of 10 nT. After the target region an output coil and another float glass neutron guide conducts the transmitted neutrons to the polarization analyzer. The output coil adiabatically rotates the x component of the neutron polarization by $\pm\pi/2$ in the x-y plane through modulation of the current direction in one of two orthogonal solenoids. This rotated spin component points along $\pm\hat{y}$ at the analyzer position to produce an asymmetry in the flux transmitted through the polarization analyzer given by $\frac{N_+ - N_-}{N_+ + N_-} = \langle PA \sin\phi \rangle$, where PA is the product of the neutron polarization from the polarizer and the analyzing power of the analyzer, ϕ is the neutron spin rotation angle, and N_+ and N_- are the count rates for $+$ and $-$ states of the output coil. The average is taken over the neutron velocity spectrum of the beam. The ion chamber operates in current mode using the $n + {}^3\text{He} \to {}^3\text{H} + p$ reaction and possesses four charge-sensitive collection plates along the beam direction with each plate subdivided into four quadrants [42].

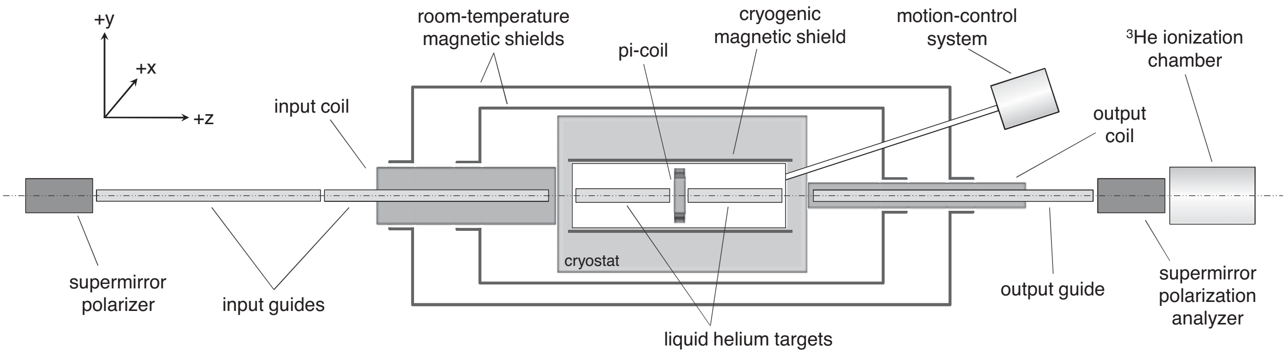

FIG. 1. Overview of an apparatus to measure PV neutron spin rotation in liquid helium.

A data-acquisition system initiates liquid helium motion, reverses the output coil and π coil fields periodically, and reads the accumulated charge from all 16 neutron signals from the ion chamber every second. A spin rotation angle is determined from each pair of output coil states $(+\pi/2, -\pi/2)$; reversing the π-coil current cancels any unintended neutron spin rotations from stray fields outside the coil. Ten rotation angles are averaged together to determine an average angle for each of a sequence of three π-coil current states $(-, 0, +)$, which is repeated five times to form a 300-s target sequence. The liquid helium is then drained and filled in the complementary state in 300–350 s, and the previous sequence is repeated to form a target cycle. The polarizer-analyzer product PA needed to infer the rotation angles was measured periodically during the experiment for all 16 ion chamber segments by introducing known misalignments between the polarization analyzer axis and the neutron spin transport coil. The parity-odd spin rotation angle is constructed from the angles measured in the left and right target chambers and in the $+$ and $-$ π-coil states. A π-off rotation angle is constructed from the angles measured with no current in the π-coil; this asymmetry must give zero in the absence of systematic errors.

The liquid helium data were collected in three reactor cycles between January and May 2008, and a fourth cycle in June 2008 was used to further explore possible systematic effects. After applying cuts to the data based on the measured neutron transmission asymmetry between target states and the target liquid levels, the remaining data comprised 5406 distinct target states. Possible false effects from slow drifts in the polarimetry were suppressed by analyzing the time sequence of asymmetries with an algorithm which cancels linear and quadratic time-dependent effects [43]. This analysis completely suppresses linear time-dependent drifts from magnetic field fluctuations at the target motion frequency (which otherwise could generate a systematic error) and also reduces the overall statistical uncertainty of the angle measurement by about 10%.The left-right beam and target segmentation was essential to suppress common-mode nonstatistical noise from reactor power fluctuations in the 1-Hz frequency bandwidth of the rotation angle measurements. The noise was reduced by a factor of 8 [37]. The statistical uncertainty from the distribution of asymmetries is ≈15% larger than would be expected from neutron counting statistics; about 8% of this extra noise comes from magnetic field fluctuations not removed by the filtering algorithm and a few percent comes from the current-mode operation of the ion chamber.

Figure 2 shows the distribution of spin rotation angle measurement in both π-coil states. The distributions show no evidence of deviations from the expected Gaussian form. The measured π-coil off angle of $[-1.2 \pm 10.0(\text{stat.})] \times 10^{-7}$ rad/m, which is interleaved between the π-coil on measurements, places an upper bound on the sum of all systematic effects. It is about a factor of 4 more sensitive than the π-on data to any systematic effects coupled to a constant longitudinal magnetic field but is not sufficiently precise to reduce the systematic uncertainty to the required level. This was done in separate measurements and calculations.

Systematic effects. We conducted a detailed analysis of a large group of identified systematic effects that could potentially cause a false asymmetry and performed auxiliary measurements to amplify and place upper bounds on their size [44]. These estimates and the results of the auxiliary measurements are listed in Table I. The auxiliary measurements were conducted in a time short compared to the measurement time and were used to determine the systematic uncertainty. The measured upper bounds were consistent with both analytical estimates and Monte Carlo simulations using the measured neutron beam and polarimeter properties and the known neutron scattering properties of liquid helium.

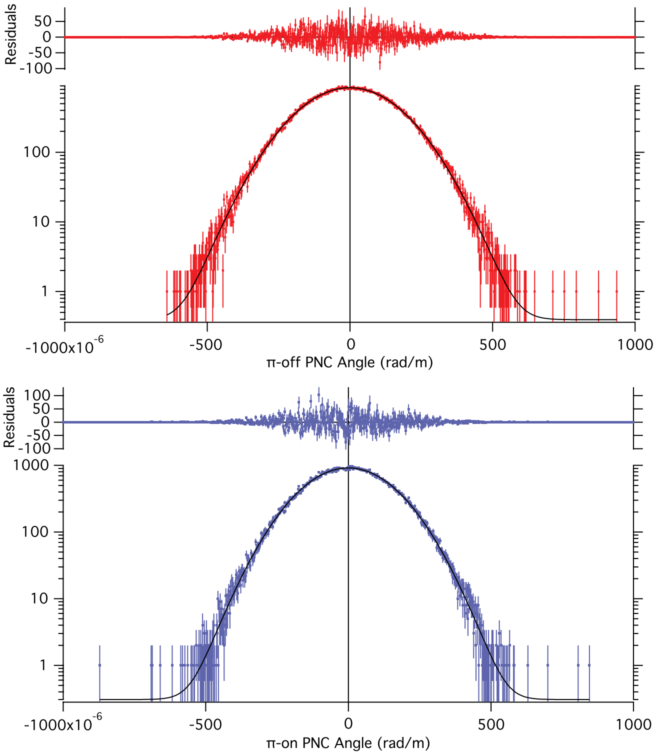

FIG. 2. (Color) Distribution of measured spin rotation angles per meter in liquid ^{4}He with π-off (upper plot) and π-on (lower plot). The solid lines are fits to a Gaussian distribution with a constant background.

TABLE I. A list of sources for potential systematic effects and estimates for the uncertainties. The values for the uncertainties either originate from a calculation or are the result of a direct measurement that places an upper bound on the effect.

Source	Uncertainty (rad/m)	Method
liquid ^{4}He diamagnetism	2×10^{-9}	calc.
liquid ^{4}He optical potential	3×10^{-9}	calc.
neutron E spectrum shift	8×10^{-9}	calc.
neutron refraction/reflection	3×10^{-10}	calc.
nonforward scattering	2×10^{-8}	calc.
polarimeter nonuniformity	1×10^{-8}	meas.
B amplification	$<4 \times 10^{-8}$	meas.
B gradient amplification	$<3 \times 10^{-8}$	meas.
PA/target nonuniformity	6×10^{-8}	meas.
Total (from measurements)	1.4×10^{-7}	

Three major classes of phenomena which can generate a nonzero false asymmetry are (1) nonforward scattering from the liquid helium coupled with the 10-nT residual internal magnetic fields and field gradients and the different phase space acceptance for the two target positions, (2) correlated nonuniformities of the polarimeter and neutron beam phase space in the two subbeams, and (3) neutron optical effects. The upper bounds on systematics in class (1) are set in auxiliary measurements with amplified magnetic field and field gradients. They are consistent with both detailed simulations and an order-of-magnitude estimate from the product of the typical difference in rotation angle between the upstream and downstream targets ($<10^{-2}$ rad) and the measured asymmetry in the transmitted intensity through the polarimeter in the two target states $(+1.0 \pm 2.2) \times 10^{-6}$. Upper bounds on systematics in class (2) were set by amplifying the sensitivity of the polarimeter to such effects by introducing large known misalignments of the polarizer and analyzer axes. Systematics in class (3) are calculable and include the target-correlated extra magnetic spin rotation from the slowing of the beam in the neutron optical potential of the helium and the target-correlated modification of the local magnetic field from helium diamagnetism.

Conclusion. Our result for the neutron spin rotation angle per unit length in ^{4}He, $d\phi/dz = [+1.7 \pm 9.1(\text{stat.}) \pm 1.4(\text{sys.})] \times 10^{-7}$ rad/m, is consistent with zero and with a previous unpublished result [45]. The cryogenic reliability of the apparatus was improved (at the cost of a somewhat slower motion of the liquid by the pump) and a fuller exploration of possible systematic effects in the neutron polarimetry was performed to achieve an improved result.

$d\phi/dz$ in n-^{4}He has been related to existing measurements of nuclear parity violation in a model [16] which subsumes many poorly understood short-range NN effects by expressing parity-odd amplitudes in terms of isoscalar $(X_n + X_p)$ and isovector $(X_n - X_p)$ one-body potentials. n-^{4}He spin rotation is interesting within the context of this model since it determines X_n. Within this model measurements in ^{18}F [18] constrain $X_n - X_p$ and measurements in odd-proton systems such as p-^{4}He [46,47] and ^{19}F [48] constrain X_p. The prediction in this model for n-^{4}He spin rotation is $d\phi/dz = (-6.5 \pm 2.2) \times 10^{-7}$ rad/m.

More theoretical work which will impact the interpretation of this measurement is in progress. Newer theoretical approaches based on effective field theory [7,9,10] that incorporate the chiral symmetry of QCD are under construction. A calculation of $d\phi/dz$ in n-^{4}He using Greens function Monte Carlo techniques now in progress [49] should greatly improve the precision of the relative weighting with which the different amplitudes contribute.

A second phase of the measurement is planned at a more intense neutron beam under construction at NIST [50]. We plan to improve the apparatus by using better-optimized magnetic shielding and control of external field fluctuations, an improved liquid helium pump and a helium liquifier to reduce deadtime, a neutron polarizer and analyzer of improved phase space uniformity, and supermirror input and output guides. We expect to reduce the statistical uncertainty on $d\phi/dz$ to 2×10^{-7} rad/m with smaller systematic uncertainties. This precision would strongly constrain NN weak amplitudes.

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[1] F. C. Michel, Phys. Rev. **133**, B329 (1964).
[2] L. Stodolsky, Nucl. Phys. B **197**, 213 (1982).
[3] M. Forte *et al.*, Phys. Rev. Lett. **45**, 2088 (1980).
[4] B. R. Heckel *et al.*, Phys. Lett. B **119**, 298 (1982).
[5] B. R. Heckel *et al.*, Phys. Rev. C **29**, 2389 (1984).
[6] S. C. Pieper and R. B. Wiringa, Annu. Rev. Nucl. Part. Sci. **51**, 53 (2001).
[7] S. L. Zhu *et al.*, Nucl. Phys. A **748**, 435 (2005).
[8] M. J. Ramsey-Musolf and S. Page, Ann. Rev. Nucl. Part. Sci. **56**, 2 (2006).
[9] C.-P. Liu, Phys. Rev. C **75**, 065501 (2007).
[10] D. R. Phillips, M. R. Schlinder, and R. P. Springer, Nucl. Phys. A **822**, 1 (2009).
[11] R. Schiavilla, M. Viviani, L. Girlanda, A. Kievsky, and L. E. Marcucci, Phys. Rev. C **78**, 014002 (2008).
[12] W.-Y. P. Hwang and C.-Y. Wen, Phys. Rev. C **78**, 025501 (2008).
[13] J. W. Shin, S. Ando, and C. H. Hyun, Phys. Rev. C **81**, 055501 (2010).
[14] B. Desplanques, J. F. Donoghue, and B. R. Holstein, Ann. Phys. (NY) **124**, 449 (1980).
[15] E. G. Adelberger and W. C. Haxton, Annu. Rev. Nucl. Part. Sci. **35**, 501 (1985).
[16] B. Desplanques, Phys. Rep. **297**, 1 (1998).
[17] L. Stodolsky, Phys. Lett. B **50**, 352 (1974).
[18] C. A. Barnes *et al.*, Phys. Rev. Lett. **40**, 840 (1978); S. A. Page *et al.*, Phys. Rev. C **35**, 1119 (1987); H. C. Evans *et al.*, Phys. Rev. Lett. **55**, 791 (1985); M. Bini, T. F. Fazzini, G. Poggi, and N. Taccetti, *ibid.* **55**, 795 (1985).
[19] W. C. Haxton, Phys. Rev. Lett. **46**, 698 (1981).
[20] J. F. Donoghue, E. Golowich, and B. Holstein, Phys. Rep. **31**, 319 (1986).
[21] S. R. Beane and M. J. Savage, Nucl. Phys. B **636**, 291 (2002).
[22] D. H. Beck and R. D. McKeown, Annu. Rev. Nucl. Part. Sci. **51**, 189 (2001).
[23] E. J. Beise, M. L. Pitt, and D. T. Spayde, Prog. Nucl. Part. Phys. **54**, 289 (2005).
[24] J. D. Bowman, G. T. Garvey, and M. B. Johnson, Annu. Rev. Nucl. Part. Sci. **43**, 829 (1993).
[25] S. Tomsovic, M. B. Johnson, A. Hayes, and J. D. Bowman, Phys. Rev. C **62**, 054607 (2000).
[26] Y. B. Zeldovich, Sov. Phys. JETP **6**, 1184 (1957).
[27] V. V. Flambaum and I. B. Khriplovich, Sov. Phys. JETP **52**, 835 (1980).

[28] C. S. Wood *et al.*, Science **275**, 1759 (1997).
[29] K. Tsigutkin *et al.*, Phys. Rev. Lett. **103**, 071601 (2009).
[30] G. Prezeau, M. Ramsey-Musolf, and P. Vogel, Phys. Rev. D **68**, 034016 (2003).
[31] G. S. Danilov, Phys. Lett. **18**, 40 (1965).
[32] J. M. Potter *et al.*, Phys. Rev. Lett. **33**, 1307 (1974).
[33] R. Balzer *et al.*, Phys. Rev. Lett. **44**, 699 (1980).
[34] S. Kistryn *et al.*, Phys. Rev. Lett. **58**, 1616 (1987).
[35] P. D. Eversheim *et al.*, Phys. Lett. B **256**, 11 (1991).
[36] V. Dmitriev *et al.*, Phys. Lett. **125**, 1 (1983).
[37] C. D. Bass *et al.*, Nucl. Inst. Methods A **612**, 69 (2009).
[38] W. M. Snow, Nucl. Inst. Methods A **611**, 248 (2009).
[39] J. S. Nico *et al.*, J. Res. NIST **110**, 137 (2005).
[40] O. Schaerpf, Physica B **156–157**, 631 (1989); **156–157**, 639 (1989).
[41] M. Forte, in *Physics with Reactor Neutrons and Neutrinos*, edited by T. Von Egidy, Inst. Phys. Conf. Ser. **42**, 80 (1978).
[42] S. Penn *et al.*, Nucl. Inst. Methods A **457**, 332 (2001).
[43] H. E. Swanson and S. Schlamminger, Meas. Sci. Technol. **21**, 115104 (2010).
[44] A. Micherdzinska *et al.*, Nucl. Inst. Meth. A, in press, doi:10.1016/j.nima.2010.11.105.
[45] D. Markoff, Ph.D. thesis, University of Washington, 1997.
[46] J. Lang *et al.*, Phys. Rev. Lett. **54**, 170 (1985).
[47] J. Lang *et al.*, Phys. Rev. C **34**, 1545 (1986).
[48] K. Elsener *et al.*, Phys. Rev. Lett. **52**, 1476 (1984).
[49] R. Schiavilla (private communication, 2010).
[50] J. C. Cook, Rev. Sci. Instrum. **80**, 023101 (2009).