$=\frac{1}{4}(x+1)$, $y=\frac{1}{6}(1-r)$, $y=\frac{1}{12}(1+3x+2r)$; (d) $y=(27-44x-s)/28$.

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First Measurement of Parity-Nonconserving Neutron-Spin Rotation: The Tin Isotopes

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A parity-nonconserving (PNC) neutron-spin rotation, φ_{PNC}, for neutrons passing through matter due, presumably, to the weak interaction is observed for the first time. For tin isotopes, the following values for φ_{PNC} in 10^{-6} rad/cm are found: ^{124}Sn, $+0.48\pm1.49$; ^{117}Sn, $+36.7\pm2.7$; and natural Sn, $+4.95\pm0.93$, with the positive sign corresponding to a right-handed rotation about the momentum. Evidence in ^{117}Sn for a larger total cross section for positive-helicity neutrons than for negative-helicity ones is also reported.

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The propagation of a beam of cold ($\lesssim 10^{-2}$ eV) neutrons through a homogeneous medium can be described by a complex wave number k:

$$k=k_0 n=k_0[1+(2\pi/k_0^2)\rho f(0)], \tag{1}$$

where k_0 is the wave number in vacuum, n is the neutron index of refraction,[1] ρ is the atomic-number density of the medium, and $f(0)$ is the coherent forward-scattering amplitude of the atomic species. Inclusion of the weak interaction in the description of the neutron scattering process gives the scattering amplitude a small parity-nonconserving (PNC) component: $f(0)=f_{PC}(0)+f_{PNC}(0)$. For an unpolarized medium,

$$f_{PNC}(0)=G'\langle\vec{\sigma}_n\cdot\vec{p}_n\rangle, \tag{2}$$

where $\vec{\sigma}_n$ is the Pauli spin of the neutron, $\vec{p}_n$ is the linear momentum in units of $\hbar=c=1$, and where the constant of proportionality, G', is expected to be of order G, the weak-coupling constant[2,3] as in Eq. (4) below.

Two PNC effects immediately emerge. $\mathrm{Im}[f_{PNC}(0)]$ describes a different attenuation length (different total cross section) for the two neutron helicity states, phenomenologically similar to circular dichroism in optics. $\mathrm{Re}[f_{PNC}(0)]$ causes the two helicity states to accumulate different phases upon passage through the medium: $\Delta(\text{phase})=\mathrm{Re}(k_+-k_-)l$, where $\pm$ refer to the helicity eigenvalues, and l is the length of the medium. A neutron with spin initially transverse to its momentum, for example, in spin state $\chi_i=|+\rangle+|-\rangle$, leaves the medium in spin state $\chi_f=e^{i\Phi}[|+\rangle+e^{i\Delta}|-\rangle]$. That is, the spin undergoes a PNC rotation, φ_{PNC}, in the transverse plane:

$$\varphi_{PNC}=\Delta=-4\pi\rho l\,\mathrm{Re}(G'),\quad \hbar=c=1. \tag{3}$$

If materials with PNC molecular or magnetic structures are avoided, there will, in general, be three contributions to φ_{PNC}: (i) the "direct" neutron-nucleon weak interaction discussed by Michel[2] and Stodolsky[3]; (ii) the neutron-electron weak interaction[3]; and (iii) the strong interaction of the neutron with parity impurities in the target nucleus as discussed by Barroso and Tadic.[4] Following Stodolsky,[3] to evaluate G' for effects (i) and (ii), the rotation is

$$\varphi_{\rm PNC} = \sqrt{2}G[C_e Z + \eta(C_p Z + C_n N) + \alpha(Z,N)]\rho l, \quad (4)$$

where Z and N are the number of electrons (protons) and neutrons in the atom; C_e, C_p, and C_n are effective "weak charges." The distortion factor, η, is a measure of the distortion of the neutron wave function in the presence of the strong interaction and $\alpha(Z,N)$ is the contribution from parity impurities in the target nucleus.

The nuclear scattering of cold neutrons is almost entirely s wave. As an admixture of p wave is required for PNC spin rotation, it has been argued[5,6] that in the vicinity of a single-particle p-wave resonance, effect (i) would be enhanced in direct proportion to the amount of p-wave amplitude available for mixing. In a simple single-particle scattering model[5] on the low-energy tail of a p-wave resonance, the distortion factor, η, is enhanced by $3\Gamma_n/2E_r K_r{}^3R^3$, where Γ_n is the particle width of the resonance, E_r and K_r are the resonance energy and wave number, and R is the nuclear radius. For ^{124}Sn, which has a p-wave resonance at 62 eV and neutron width of 6 meV, η becomes $\simeq 200$. As Sn is also a good neutron transmitter, our search for $\varphi_{\rm PNC}$ began in ^{124}Sn, with natural Sn as a reference. Preliminary measurements showed no rotation in ^{124}Sn, but unexpectedly showed a rotation with the natural Sn being used as a reference.[7] These results led us to investigate ^{117}Sn as a source of an enhanced $\varphi_{\rm PNC}$ in light of the large neutron-capture γ-ray asymmetry reported for this isotope.[8,9]

The experiment was performed at the Institut Laue-Langevin high-flux reactor in Grenoble. Most of the data was accumulated on the S-43 monochromatic 7-Å neutron beam (neutron flux approximately 10^7/cm^2 • sec). The experimental apparatus was a precision neutron polarimeter based upon the "crossed polarizer" technique familiar from optics. Neutron polarization (91%) was achieved by reflection from magnetically saturated Fe-Co films that had been evaporated onto TPX (CH_2) plastic sheets.[10]

Figure 1 shows a schematic view of the apparatus. The polarizer and analyzer (identical) are enclosed in magnet boxes that return the flux of the 1 kG saturation field. In both cases, the field is along the $\hat{Z}$ axis. Upon leaving the polarizer, the neutrons enter an open-ended "input-coil," whose increasing vertical magnetic fields add to the decaying leakage field of the magnet box, providing a 10-G vertical guide field that preserves the neutron polarization. The exit of the input coil acts as a current sheet to allow the neutrons to enter the low-field target region nonadiabatically, with spins along $\hat{Z}$.

The output coil is identical to the input coil, but rotated by $\pi/2$ to position its magnetic field to lie along $\hat{Y}$. The aim is to turn smoothly the magnetic field direction from $\hat{Y}$ at the current sheet side of the output coil to the $\hat{Z}$ direction of the analyzer magnet box. To achieve a smooth turn, soft iron shims are used to extend the analyzer field further into the output coil. The depolarization that results from neutron spins not following the adiabatic turning of the magnetic field direction is less than 0.1%. By reversing the current sense in the output coil, the neutron

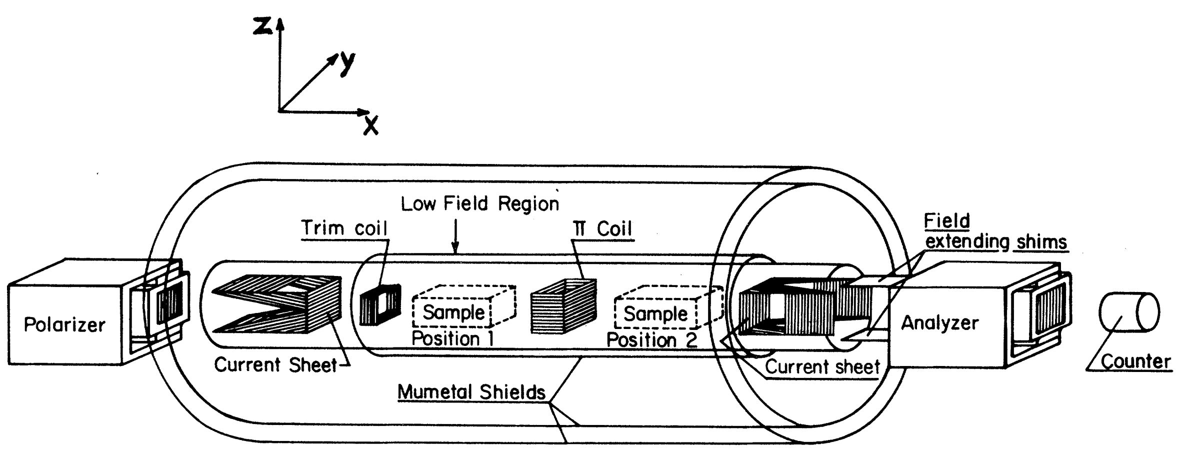

FIG. 1. Schematic view of experimental apparatus. The neutron beam polarization is along $\hat{Z}$ and momentum along $\hat{X}$.

spins can be adiabatically rotated by $\pm\pi/2$. The result of this arrangement is a crossed polarizer configuration (analogous to optical polarizers crossed at 45°).

The target region is maintained at low magnetic field (< 5 mG) by three layers of magnetic shielding. In this region are two sample positions, 20 cm apart, separated by a rectangular solenoid (π coil) whose magnetic field is directed along $\hat{Z}$. The magnetic field strength in the π coil is such that neutron spins undergo a Larmor precession of π radians upon passage through the coil. Any rotation of a neutron spin in the Y-Z plane (see Fig. 1) caused by the sample is reversed in sign upon moving the sample to opposite sides of the π coil. In this way, changes in count rates are minimized, and rotations caused by residual magnetic fields (unchanged when the sample is moved) are cancelled to first order. The neutron counter is a ^{6}Li-doped glass scintillator optically coupled to a photomultiplier. The counting rate was typically 2×10^{4} n/sec.

The dimensions and isotopic content of the samples used are listed in Table I. The samples were measured to be nonmagnetic to less than 2×10^{-5} G at their surface, and numerous reversals of sample orientation were made as a systematic test. Our major null test consisted of accumulating half of the data with the center π coil turned off. Any asymmetric scattering effects coupled to inhomogeneous magnetic fields or general apparatus asymmetries are revealed in this way. To ensure that leakage fields from the π coil did not introduce troublesome inhomogeneous magnetic fields, the data runs were alternated with the current in the π coil reversed. Additional null tests included running the experiment with double the current in the π coil ($\pm 2\pi$ rotation), and repeating the measurement with empty sample holders.

The experimental procedure was then as follows.

TABLE I. Dimensions and isotopic content of the Sn samples.

Sample	Dimensions (mm^3)	Isotopic content ^{124}Sn	^{117}Sn
^{124}Sn[a]	11×11×49.5	93.28%	0.49%
^{117}Sn[b]	11×11×60.0	0.21%	84.23%
Natural Sn	11×11×49.5	5.94%	7.61%[b]
Natural Sn	11×11×53.5	5.94%	7.61%[b]

[a]Obtained from Oak Ridge National Laboratory.
[b]Ref. 13.

The current in the output coil was reversed every 1.23 sec, and the sample position reversed every sixty-four such spin flips. Two days of sample reversals would constitute one data cycle. There would be four such data cycles to each measurement: two with the π coil off and one each with the π coil causing a $+\pi$ and $-\pi$ Larmor precession. After the eight day measurement, the samples would be removed, changed in orientation, and a new measurement begun. A summary of the data obtained is given in Fig. 2.

After correcting for the isotopic purity of the enriched isotopes, and subtracting the contribution of the ^{117}Sn content in the ^{124}Sn, the results obtained are

$$\varphi_{PNC}(^{124}\mathrm{Sn}) = (+0.48\pm1.49)\times10^{-6}\ \mathrm{rad/cm},$$
$$\varphi_{PNC}(^{117}\mathrm{Sn}) = (+36.7\pm2.7)\times10^{-6}\ \mathrm{rad/cm},$$
$$\varphi_{PNC}(\mathrm{natural\ Sn}) = (+4.95\pm0.93)\times10^{-6}\ \mathrm{rad/cm}.$$

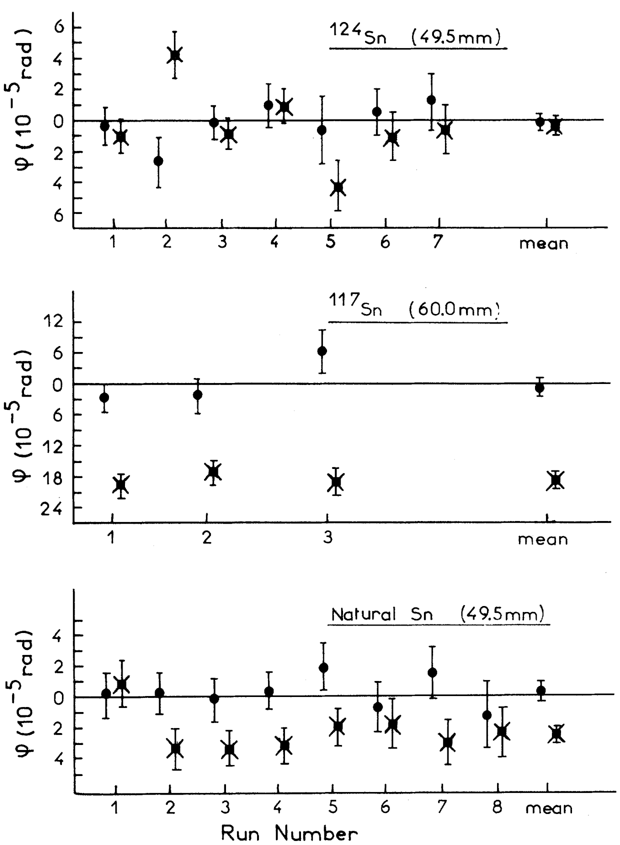

FIG. 2. Summary of the Sn data. Each pair of points represents an eight day measurement. The data points marked by a dot represent the four day average of the null test (π coil off). The points marked by a crossed square are the average of the data taken with a $+\pi$ and $-\pi$ precession in the π coil. All error bars are 1σ statistical errors.

The positive sign of φ_{PNC} corresponds to a right-hand rotation of the neutron spin around its momentum vector. Equivalently, referring to Eqs. (1–3), $\mathrm{Re}(G')<0$.

Subtracting from φ_{PNC}(natural Sn) the contribution from the 7.61% of ^{117}Sn in the sample leaves a residual rotation of $(2.16\pm0.95)\times10^{-6}$ rad/cm. We intend in the future to improve the statistical accuracy of the natural-Sn results to determine whether another of the Sn isotopes also contributes an enhanced PNC rotation.

In a model, whereby the large rotation in ^{117}Sn is explained by the mixing of a nearby negative-parity neutron resonance with the predominant s-wave scattering, $\mathrm{Im}[f_{PNC}(0)]$ and $\mathrm{Re}[f_{PNC}(0)]$ would both be enhanced. A simple modification of our apparatus allowed us to attempt to measure $\mathrm{Im}[f_{PNC}(0)]$. In Fig. 1, the trim coil current was set to rotate the neutron spins by $\pi/2$, into the $\hat{Y}$ direction. The current in the π coil was adjusted to cause another Larmor precession of $\pi/2$, putting the neutron spins along $\hat{X}$. Reversal of the π coil current thus reversed the neutron helicity. The ^{117}Sn sample was fixed in sample position 2, and with the output coil and analyzer removed the π current was reversed every 1.23 sec. Hence, the helicity dependence of the neutron transmission through the target was measured. A null test was performed by repeating the measurement with an unpolarized beam (residual polarization < 0.2%). Defining $A_n=(N_+-N_-)/P(N_++N_-)$, where $P=90\%$ is the beam polarization, and $N_\pm$ are the count rates for helicity $\pm$, we found

$$A_n(60\text{ mm }^{117}\mathrm{Sn})=(-9.78\pm4.01)\times10^{-6},$$

$$A_n(\text{null test})=(-2.99\pm5.33)\times10^{-6}.$$

The negative sign corresponds to $\mathrm{Im}(G')>0$. We do not cast A_n in terms of a helicity-dependent neutron cross section because the results are preliminary and the large errors preclude a definitive value.

The large PNC rotation in ^{117}Sn is consistent with the neutron-capture γ-ray asymmetry, $A_\gamma=(4.4\pm0.6)\times10^{-4}$,[8,9] if one assumes that the parity nonconservation occurs in the caputre (scattering) state rather than the ground state of ^{118}Sn. Under this assumption, it is possible to establish relations between the two effects.[11,12] There are two important differences, however. φ_{PNC} could arise from either or both of the $J=0$ and $J=1$ scattering channels (^{117}Sn has spin $\frac{1}{2}$), while A_γ sees only the $J=1$ channel. In addition, the spin-rotation phenomenon involves only continuum (unbound) neutron-nuclear states. Strong-interaction effects are then, in part, determined by measurable scattering parameters.

φ_{PNC} and A_γ are in this sense complementary and it is possible that a detailed comparison may lead to a better understanding of the source of the enhanced PNC effects in this nucleus. In a model whereby the enhancement is caused by the mixing of a nearby 1^- resonance into the 1^+ scattering channel, the relative sign difference between $\mathrm{Re}[f_{PNC}(0)]$ and $\mathrm{Im}[f_{PNC}(0)]$ that is implied by our measurement of A_n would indicate that the 1^- level lies below the neutron threshold $\{f(0)\propto\Gamma_n/[E-E_R+\frac{1}{2}i\Gamma_{tot}]\}$.

In conclusion, we have demonstrated that PNC neutron-spin rotation is a viable tool for the study of PNC effects in nuclei. The results are complementary to those of the more standard techniques of circular polarization and γ-ray asymmetry following neutron capture. One could expect to investigate nuclei in which the standard techniques are inapplicable. The absence of spurious systematic effects at the level of 4×10^{-6} rad bodes well for future experiments of this nature.

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Polarization of Muoproduced $J/\psi(3100)$

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The polarization and Q^2 dependence of muoproduced $\psi\to\mu^+\mu^-$ have been analyzed in a magnetized-steel calorimeter at Fermilab. The reaction $\gamma_V N\to\psi N$ is found to be helicity conserving. Even after allowance for possible Q^2 dependence of the decay angular distribution, the ψ muoproduction cross section falls more steeply in Q^2 than predicted by ψ dominance.

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We have measured the polarization of $J/\psi(3100)$ produced by 209-GeV muons, analyzed by the decay $\psi\to\mu^+\mu^-$. These are the first data on the polarization of any charmonium state produced by real- or virtual-photon–nucleon collisions. Measurement of the ψ polarization is an essential component of the study of ψ-leptoproduction mechanisms, which was begun[1] with a subset of these data. If ψ-N elastic scattering is helicity conserving, the polarization of elastically leptoproduced ψ's in the vector-meson–dominance (VMD) picture[2] is simply related to that of the exchanged photon. In this case, the data measure R, the ratio σ_L/σ_T of ψ-production cross sections by longitudinally and transversely polarized virtual photons (γ_L and γ_T). Since R must vanish at $Q^2=0$, it is a function of Q^2 which must be incorporated in any complete description of the Q^2 dependence of ψ leptoproduction.

The magnetized-iron multimuon spectrometer and ψ reconstruction analysis have been described.[1] With a slightly different analysis, the dimuon mass spectrum of $\approx 10^6$ trimuon final states (75% of the data) has been published.[3] The present 2500-event (ψ and ψ') sample, based on the same data, is more tightly cut. The sample is characterized as elastically produced, with events depositing less than 4.5 ± 2.5 GeV in the calorimeter. The real and Monte Carlo- (MC) simulated widths of the ψ mass peak are 8.8% and 8.3% rms, respectively. After the production mechanisms in the simulation are adjusted to yield detailed agreement with the data, the calculated average efficiency for detection and analysis of ψ's elastically produced within the fiducial target is 21%.

The angular distributions of the decay products of electroproduced lower-mass vector mesons[4] have shown the production process to be consistent with s-channel helicity conservation (SCHC) and natural parity exchange (NPE). With these assumptions, the distribution of dimuons from ψ

