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Measurement of parity nonconserving neutron spin rotation in lanthanum

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The rotation, $\phi_{\rm pnc}$, of a neutron beam polarization vector due to parity nonconserving forces is measured in a lanthanum target. It is found that $\phi_{\rm pnc}/l = -(21.9\pm2.9)\times10^{-5}$ rad/cm, where the negative sign corresponds to a left-handed rotation of the neutron spin about its momentum.

In the vicinity of a neutron p-wave resonance, the violation of parity invariance can be enhanced by several orders of magnitude. One of the most striking examples of such enhancement is the 0.75 eV p-wave resonance in ^{139}La for which the relative change in total resonant neutron scattering cross section upon reversal of the neutron helicity, $P(E_R)=(\sigma_+-\sigma_-)/(\sigma_++\sigma_-)$ for $E_R=0.75$ eV, was found to be[1] $(7.3\pm0.5)\times10^{-2}$. The parity nonconserving (pnc) behavior of the low energy wing of this resonance in lanthanum has been studied in several ways with thermal neutrons. The correlation A_γ between the neutron spin and the directions of γ rays emitted after polarized thermal neutron capture was measured to be[2] $A_\gamma=(-17.2\pm2.2)\times10^{-6}$. The circular polarization P_γ of the γ rays following thermal neutron capture was found to be[2] $P_\gamma=(-16.0\pm2.5)\times10^{-5}$. Finally, the relative change in total cross section upon reversal of the neutron helicity was measured to be[3]

$$P(E_0=0.025\text{ eV})=(9.0\pm1.4)\times10^{-6}\ .$$

Although each of the above pnc asymmetries occurs in the inelastic (capture) channel, the measurements are complementary in the sense that they emphasize different components of the ^{140}La compound state.

The pnc interaction can be studied in the elastic scattering channel as well through the measurement of the pnc neutron spin rotation. Briefly stated, the coherent forward scattering amplitude $f(0)$ of a neutron wave propagating through a material target, in the presence of a pnc interaction, will acquire a pnc component which can be written as

$$f_{\rm pnc}(0)=G'\langle\vec{\sigma}_{\rm n}\cdot\vec{\rm p}_{\rm n}\rangle\ , \tag{1}$$

where $\vec{\sigma}_{\rm n}$ is the Pauli spin and $\vec{\rm p}_{\rm n}$ the linear momentum of the neutron, and where G', which can be complex, is the pnc amplitude. The imaginary part of Eq. (1) describes the helicity dependent scattering cross section already mentioned. The real part of Eq. (1) indicates a different phase velocity for the two neutron helicity states which is equivalent to a rotation of the neutron spin about its momentum vector. For neutron propagation through a target of length l, the total angle of rotation $\phi_{\rm pnc}$ of the neutron spin in the plane perpendicular to $\vec{\rm p}_{\rm n}$ is given by

$$\phi_{\rm pnc}=-4\pi\rho l\,{\rm Re}(G')\ , \tag{2}$$

where ρ is the atomic number density of the target material.[4,5]

Using a neutron polarimeter that is described in previous publications,[6,7] we have measured $\phi_{\rm pnc}/l$ for subthermal neutron propagation through natural lanthanum targets (99.9% ^{139}La). The experiment was performed at the monochromatic 7.2 Å neutron beam station (S43) at the Institut Laue-Langevin high flux reactor. The polarimeter consists of a magnetically shielded target region that is sandwiched between two "supermirror" neutron polarizers[8] that are used as a crossed polarizer-analyzer pair. The polarization product of the polarizer-analyzer pair (for polarization vector ⊥ to $\vec{\rm p}_{\rm n}$) under operating conditions of the polarimeter was 95.0%.

The target region is shown schematically in Fig. 1 (for more details see Refs. 6 and 7). The neutron beam travels along the $\hat{X}$ axis and enters the target region with spins polarized along the $\hat{Z}$ axis. The target is periodically moved between positions 1 and 2, on opposite sides of a fixed central solenoid (π coil). The current in the π coil is set so

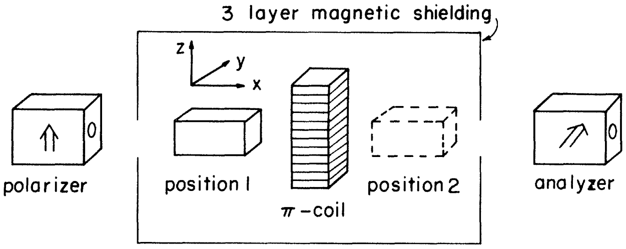

FIG. 1. The target is alternated between positions 1 and 2. The π coil rotates the neutron spins by π radians about the $\hat{Z}$ axis. The analyzer senses small rotations of the neutron spin in the YZ plane.

TABLE I. Experimental results. The errors listed are one standard deviation statistical errors.

$\phi \times 10^{-5}$ rad	1.5 cm La	0.75 cm La
$\phi_{\text{int}} = \phi_{\text{pnc}} + \phi_{\text{pc}}$	-46.3 ± 4.0	14.8 ± 2.4
$\phi'_{\text{int}} = \phi_{\text{pnc}} - \phi_{\text{pc}}$	-21.2 ± 4.1	-46.4 ± 2.3
ϕ_{pc}	-12.6 ± 2.9	30.6 ± 1.7
ϕ_{pnc}	-33.8 ± 2.9	-15.8 ± 1.7
ϕ_{pnc}/l	-22.5 ± 1.9	-21.1 ± 2.2

that the neutron spins Larmor precess by π radians upon passage through the coil. With the target in position 2, the neutron spins will undergo a rotation ϕ_{int} within the target, and a rotation ϕ_{ext} due to residual magnetic fields external to the target, and a total rotation, $\phi_{\text{ext}}+\phi_{\text{int}}$, is measured. With the target in position 1, ϕ_{ext} is unchanged to first order, while ϕ_{int} is reversed in sign by the π coil, resulting in a measured rotation equal to $\phi_{\text{ext}}-\phi_{\text{int}}$. In this way ϕ_{ext} and ϕ_{int} can be distinguished. By reversing the current in the π coil and by taking additional data with the π coil turned off, we have shown that it is possible to measure separately ϕ_{int} and ϕ_{ext} to within at least 4×10^{-6} rad.[7] During the course of a measurement, ϕ_{ext} is monitored to look for magnetic field drifts, while ϕ_{int} contains the pnc rotation that is sought.

For the targets which have been examined, $\phi_{\text{int}} < 10^{-3}$ rad, which allows it to be decomposed as

$$\phi_{\text{int}} = \phi_{\text{pnc}} + \phi_{\text{pc}} , \tag{3}$$

where ϕ_{pnc} is as defined in Eq. (2), and ϕ_{pc} is the sum of all parity conserving rotations of the neutron spin that are caused by the target. To within the accuracy of our measurements, the only contribution to ϕ_{pc} comes from ferromagnetic impurities in the target material. For example, in bismuth targets of 99.999% quoted purity, we have observed surface magnetic fields as large as 10 mG due to the accumulation of isoluble Fe impurities at the Bi crystal boundaries. To distinguish ϕ_{pnc} from rotations due to ferromagnetic impurities, the target is rotated in orientation with respect to the neutron beam. ϕ_{pnc} is independent of target orientation while ϕ_{pc} is orientation dependent. Finally, because ϕ_{pnc} is linearly proportional to the target length, targets of different length are measured as a systematic check.

The measurements were performed with two lanthanum targets, both having 1.1 cm × 1.1 cm square cross setional area, with lengths of 1.5 and 0.75 cm. The 1.5 cm long target[9] was vacuum cast to eliminate possible voids and subsequently machined to size. The 0.75 cm target[10] was machined from a block of high purity lanthanum. Both targets were tested for residual magnetization with a flux gate magnetometer. The 1.5 cm target was found to have a magnetic field of 2×10^{-5} G at a distance of 0.5 cm from its surface, while the 0.75 cm target had a field of 9×10^{-5} G at the same distance from its surface. In both cases, the field lines were dipolar in character for distances greater than 0.5 cm from the target. Because it is the component of magnetic field parallel to $\vec{p}_n$ that produces rotations, ϕ_{pc}, of the neutron spin in the plane perpendicular to $\vec{p}_n$, a rotation of the target by 180° about an axis perpendicular to $\vec{p}_n$, should to first order reverse ϕ_{pc}.

The results obtained after nine days of data collection are listed in Table I. In Table I, ϕ_{int} is the measurement for the initial target orientation, while ϕ'_{int} corresponds to the target rotated by 180° about an axis perpendicular to $\vec{p}_n$. ϕ_{pnc} and ϕ_{pc} are deduced from ϕ_{int} and ϕ'_{int}.

The last row in Table I is the pnc neutron spin rotation normalized to unit length. Because the difference between ϕ_{pnc}/l for the two targets is a measure of how well the reversal of target orientation has canceled ϕ_{pc}, we quote our results as

$$\phi_{\text{pnc}}/l\ (\text{La}) = -(21.9 \pm 2.9)\times 10^{-5}\ \text{rad/cm} ,$$

where the minus sign denotes a left-handed rotation of the neutron spin about its momentum.

The enhancement of the pnc neutron spin rotation in lanthanum over its Born approximation prediction is greater than a factor of 1000. Possible explanations for such an enhancement have all focused on the role played by different components of p-wave resonances: the mixing of single-particle components,[5,11] the coupling of potential and compound components,[12] and the compound component mixing with nearby s-wave resonances.[13,14] As a consistency check that the p-wave resonance at 0.75 eV in lanthanum is responsible for the large pnc effects seen at thermal neutron energies, a comparison can be made between $P(E_0 = 0.025\ \text{eV})$ and ϕ_{pnc}/l. Following Refs. 14 and 15, if the neutron scattering amplitude is given a Breit-Wigner form in the vicinity of the resonance, then the following equality should exist:

$$\frac{P(E_0)}{\phi_{\text{pnc}}/l} = \frac{L}{2}\frac{\Gamma_\gamma}{E_0 - E_R} , \tag{4}$$

where L is the mean free path for thermal neutrons in lanthanum, and $\Gamma_\gamma = 45 \pm 5$ meV is the gamma decay width of the resonance at $E_R = 0.75$ eV.[1] The right-hand side of Eq. (4) is equal to $-(0.057 \pm 0.006)$, while the left-hand side is equal to $-(0.041 \pm 0.008)$, in reasonable agreement with one another. The challenge remains, however, to extract the neutron-nucleus weak interaction coupling strength from these measurements.

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