Search for a Spin-Dependent Short-Range Force

The existence of possible short-range forces related to unpolarized and polarized particles has attracted the attention of physicists for decades. These forces provide a possible new source for the parity ($P$) and time reversal ($T$) symmetry violation. Moody and Wilczek [1] proposed that a macroscopic force with an interaction range from $cm$ to $\mu m$ can couple to scalar and pseudoscalar vertices through the exchange of spin-0 bosons. The scalar coupling is spin-independent and depends only on the fermion density. The pseudoscalar coupling is entirely spin-dependent. The virtual boson field of a fermion in the two cases will be monopole and dipole fields in the sense of the multiple expansion. The monopole-dipole force has the Yukawa-type interaction potential

$$V(r) = \frac{g_s g_p \hbar^2}{8 \pi m_n} (\hat{\sigma} \cdot \hat{r}) \left( \frac{1}{r \lambda} + \frac{1}{r^2} \right) \exp(-r/\lambda)$$

where $\hat{r}$ is the unit vector from the unpolarized nucleon to the polarized nucleon, $\hat{\sigma}$ is the spin of the polarized nucleon, $m_n$ is the nucleon mass, $g_s g_p$ is the product of couplings at the scalar and pseudoscalar vertices, and $\lambda$ is the force range. The spin-dependent short-range force can change the precession frequency of a polarized nucleon. The potential of the form $\hat{\sigma} \cdot \hat{r}$ is similar to the potential of a magnetic dipole moment in an external magnetic field given by $\vec{\mu} \cdot \vec{B}$.

We use a high-pressure, thin-walled $^3$He cell to search for such a new interaction between polarized $^3$He nuclei and unpolarized nucleons. There are two advantages in using the $^3$He cell. High polarization of $^3$He nuclei can be achieved by the spin exchange optical pumping [2]. The thickness of the $^3$He cell window is about few hundred $\mu m$, which covers the expected force range in the sub-millimeter scale.
Figure 1: Schematic of the short-range force experiment (left) and photograph of cell and coil (right) in phase I. Helmholtz coil is installed to keep the polarization. The cylindrical cell axis is along the axis of Helmholtz coil. Correction coils (dashed-loop curves) are installed to compensate field gradients. $^3$He nuclei are polarized through the spin-exchange optical pumping with Rb and $^3$He. Pickup coil A measures the precession frequency variation due to the mass block. Pickup coil B is used as a magnetometer.

In the experiment, Zheng et al. [3] used an apparatus shown in Fig. 1 to search for the short-range force. A unpolarized mass block is placed on the end of a cylindrical cell containing polarized $^3$He gas along the axis of the cylinder. The mass block can be moved close to (mass-in) and away from (mass-out) the $^3$He cell. No mass is placed to the other end of the cylindrical cell. The precession frequency at this end is treated as a magnetometer. The effect of the short-range force can be determined by comparing the precession frequencies of these two ends, and the difference between mass-in and mass-out. Systematic uncertainties from the magnetic properties of the mass are reduced by flipping both the magnetic field and spin directions. As shown in Fig. 2, the result shows that a current best limit [5] can be approached by this setup.

In the second phase, as shown in Fig. 3, the magnetic field uniformity is improved by optimizing the position of the $^3$He cell. Two pickup coils are positioned closer to each other in order to have a better correlation. A factor of 10 improvement is expected. The sensitivity is limited by the polarization and magnetic field variation for different configurations of magnetic field and spin directions. A better sensitivity will be expected with improvement in uniformity and stability of the field.
Figure 2: Constraints on the coupling constant product $g_s g_p$ of the spin-dependent force as a function of the range $\lambda$ and the equivalent mass of the axion-like particle mediating the short-range interaction. The dashed line is the result from [4], the dash-dotted line is the reanalysis of the $T_2$ measurements of [5], the solid line is the analysis of our present experiment, and the dotted line is a projected sensitivity achievable using our method based on the stability of the magnetic field demonstrated in [6]. The dark gray is the excluded region and the light gray is the region that could be excluded with the improved field stability.

In the third phase, as shown in Fig. 4, a new solenoid coil with shielding is being designed to provide a better uniformity of magnetic field using the method in [6]. A short cylindrical $^3$He cell is built so that two mass blocks can be placed near two ends of the $^3$He cell. The short-range force has opposite effects at these two ends since it depends on the direction from polarized nuclei to unpolarized nucleons. The systematic errors due to polarization and magnetic field uncertainties can be further suppressed.

We explore a new technique to use polarized $^3$He nuclei and unpolarized nucleons to investigate the short-range force in the region which cannot be detected by traditional methods. The proposed method shows that a promising sensitivity with a factor of 10 to 100 improvement can be accomplished. Table 1 shows the modification for each phase. We predict that an even higher sensitivity can be achieved if a thinner wall for the $^3$He cell and denser material are used. This project is in collaboration with Prof. Mike Snow’s group at Indiana University.
Figure 3: Schematic of the short-range force experiment in phase II. The $^3$He cylindrical cell can be moved to where the uniformity is the best. Correction coils (dashed-loop curves) are installed to compensate field gradients.

References


Figure 4: Schematic of the short-range force experiment in phase III. A solenoid (dashed-loop curves) and a short cylindrical $^3$He cell are used to provide better uniformity and suppress systematic uncertainties.

<table>
<thead>
<tr>
<th>Status</th>
<th>Features</th>
<th>Sensitivity</th>
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<tbody>
<tr>
<td>Phase I (Accomplished)</td>
<td>Correction coils are used to compensate gradients at the two ends of the cylindrical cell. Channel A and channel B are at two ends of the cylindrical cell.</td>
<td>Around the current limit</td>
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<td>Phase II (Ongoing)</td>
<td>The position of the cylindrical cell can be adjusted. Channel A and channel B are put together.</td>
<td>A factor of 10 to 20 improvement</td>
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<tr>
<td>Phase III (R &amp; D)</td>
<td>A solenoid and a short cylindrical cell are used. Two mass blocks are installed at the two ends of the cylindrical cell.</td>
<td>A factor of 20 to 100 improvement</td>
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Table 1: Summary of each phase.