Search for an exotic parity-odd spin- and velocity-dependent interaction using a magnetic force microscope

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Exotic spin-dependent interactions may be generated by exchanging hypothetical bosons that have been proposed to solve some mysteries in physics by theories beyond the standard model of particle physics. The search for such interactions can be conducted by tabletop experiments using high precision measurement techniques. Here we report an experiment to explore the parity-odd interaction between moving polarized electrons and unpolarized nucleons using a magnetic force microscope. The polarized electrons are provided by the magnetic tip at the end of a silicon cantilever, and their polarizations are approximately magnetized in the plane of the magnetic coating on the tip. A periodic structure with alternative gold and silicon dioxide stripes provides unpolarized nucleons with periodic number density modulation. The exotic forces are expected to change the oscillation amplitude of the cantilever which is measured by a fiber laser interferometer. Data has been taken by scanning the tip over the nucleon source structure at constant separation, and no exotic signal related to the density modulation has been observed. Thus, the experiment sets a limit on the electron-nucleon coupling constant, \( g_A^e g_N^P \leq 9 \times 10^{-15} \) for 15 \( \mu m \leq \lambda \leq 180 \mu m \), using a direct force measurement method.

I. INTRODUCTION

The experimental search for the exotic spin-dependent interactions has received substantial attention in the last decade.¹,² These interactions may be mediated by hypothetical bosons such as axions,³-⁶ familyons,⁷ Majorons,⁸,⁹ arions,¹⁰,¹¹ paraPhotons,¹²-¹⁵ and new Z' bosons¹⁶-¹⁸. These new bosons are introduced in efforts to resolve some puzzles in physics such as the strong CP problem¹⁹, the nature of dark matter and dark energy²⁰, and the hierarchy problem²¹. Under the framework of quantum field theory, Dobrescu and Mocioiu derived sixteen types of interaction potentials generated by any generic spin-0 or spin-1 boson exchange assuming rotational invariance²². These potentials were re-derived and classified according to the types of physical couplings recently by Faddeev et al.²³. Except for the Yukawa-type interaction, fifteen of them are spin dependent and generated through pseudoscalar, vector or axial-vector couplings.

Among them, extensive searches²⁴,⁴⁰ have been conducted on the axion-mediated spin-mass or spin-spin exotic interactions that were initially proposed by Moody and Wilczek.¹⁷ Experimental searches have also been performed on the spin- and velocity-dependent exotic interactions¹⁸,²⁸,⁴⁵-⁴⁸,⁵³. In this paper, we explore one of them, which is parity-odd as given by

\[
V_{12+13} = g_A^e g_N^P \frac{\hbar}{4\pi} (\sigma \cdot \hat{v}) \frac{1}{r} e^{-r/\lambda},
\]

where \( \hbar \) is the reduced Planck’s constant, \( g_A^e \) is the axial-vector coupling constant to electrons, \( g_N^P \) is the vector coupling constant to nucleons, \( \sigma \) is the Pauli vector of electron spin, \( \hat{v} \) is the relative velocity between electron and nucleon, and \( \lambda = \hbar/m_N c \) is the interaction range with boson mass \( m_N \). This potential can be generated by the exchange of a massive spin-1 boson \( Z' \) in a Lorentz-invariant theory described by the Lagrangian \( \mathcal{L}_{Z'} = Z'_\mu \psi \gamma^\mu (g^{e\gamma}_e g^P_N + \gamma_5 g^{A\gamma}_e g^N_P) \psi \), here \( \psi \) denotes the fermion field. For simplicity, we assume that \( g^{e\gamma}_e = g^{P_N} = g^N_P \), where \( p \) and \( n \) denote proton and neutron, respectively.

The above potential can be treated as \( V = \gamma \hbar \sigma \cdot \hat{B}_{eff} \), and then we can see that the spin \( \sigma \) can be used to sense the effective magnetic field \( \hat{B}_{eff} \) produced by the interaction. Atomic magnetometer operating in the spin-exchange relaxation-free (SERF) regime has been used to detect the \( \hat{B}_{eff} \) produced by an unpolarized bismuth germanate insulator, and the experiment sets the strongest constraints on the coupling constant between electrons and nucleons for \( \lambda > 1 \times 10^{-4} m \).⁵⁶ The measurements of neutron spin rotation or spin relaxation rate of polarized \(^3\)He gas have also been used to constrain the possible new interaction between polarized neutrons and unpolarized matter⁵³,⁵⁴. The exchange of vector bosons between electrons and nucleons
induces parity-nonconserving effects (PNC) in atoms and molecules, which was used to constrain the parity violating vector axial-vector nucleon-electron and nucleon-proton interactions \[13\] at the nanometer range. Recently, the exotic interaction between the neutron and the matter of the Earth was sought using a spin-echo based interferometry technique \[55\]. On the other hand, spin polarized torsion pendulum is one of the most sensitive technique to search for the new interaction at centimeter scale by macroscopic torque measurement \[28, 48, 49\]. Here we use a sensitive cantilever with a magnetic tip to search for the interaction between polarized electrons and unpolarized nucleons at the micrometer scale by direct force measurement.

II. EXPERIMENTAL SCHEME

The experiment is schematically shown in Fig. 1(a). A cantilever with a magnetic tip is used as a force sensor to measure the force between the spin-polarized magnetic tip and a unpolarized nucleon source at the micrometer range. The magnetic tip is coated with hard magnetic CoCr alloy to provide spin-polarized electrons. The tip was magnetized in the perpendicular direction to the cantilever and the electron polarizations are approximately in the plane of the magnetic coating. As the \(V_{12+13}\) potential is proportional to \((\vec{\sigma} \cdot \vec{\sigma})\), the relative velocity is chosen to be along the polarization direction in order to maximize the exotic force. This is fulfilled by driving the cantilever vibrating perpendicularly. The source mass is made of alternative high density (gold) and low density (silicon dioxide) materials to create a nucleon density modulation. When the tip is oscillating over the source mass, the vibration of the cantilever is reinforced or weakened by the exotic interaction, and the oscillation amplitude changes depending on the density of the material underneath the tip. Therefore, a periodic signal correlated with the density modulation would be expected if the exotic interaction is detectable. This design helps to separate the signal of interest from the spurious signals, such as the electrostatic force and Casimir force.

The cantilever is driven by a piezo actuator at given amplitude and frequency, and its displacement is measured by a home-made fiber laser interferometer. The exotic interaction acts as an additional damping (or exciting) force proportional to the velocity of the cantilever. The equation of motion of the cantilever can be written as

\[
m\ddot{z} + m\gamma \dot{z} + k z = F_d \cos(\omega_d t) + f_s \dot{z},
\]

where \(m\), \(k\), and \(\gamma\) are the effective mass, spring constant and damping factor of the cantilever, respectively. \(F_d\) is the external driving force amplitude of the piezo, and \(\omega_d\) is the driving angular frequency. The \(f_s = F_s/v\) is the spin-dependent exotic force \((F_s)\) divided by velocity. In this study, the cantilever is constantly driven at its resonance frequency, and the cantilever’s vibrational amplitude is given by

\[
z_{amp} \approx z_{far} \left( 1 + \frac{Q\omega_0 f_s}{k} \right),
\]

where \(z_{far} = QF_d/k\) is the vibration amplitude when the magnetic tip is free from any extra interaction, which can be determined when the magnetic tip is far away from the source mass. \(Q = \omega_0/\gamma\) is the quality factor of the cantilever, \(\omega_0\) is its resonance angular frequency. To avoid the interference of constant background signals, we search for the exotic interaction by looking for the amplitude variation when the magnetic tip scans over different areas of nucleon density.

III. EXPERIMENTAL DETAILS

A. Magnetic force details

A commercially available magnetic force probe was used in this experiment \[52, 59\]. The cantilever is made of single crystalline silicon with dimension of 121.90 \(\mu m \times 34.77 \mu m \times 1.62 \mu m\) as measured by scanning electron microscopy (SEM). The eigenfrequencies of the first two bending modes were measured to be \(f_1 = 142309\) Hz and \(f_2 = 915089\) Hz, respectively. We determined the effective spring constant of the cantilever by matching the two measured eigenfrequencies to the values calculated by finite element analysis. The frequency match is achieved with a relative uncertainty of 1.9% by only tuning the cantilever thickness to 1.415 \(\mu m\) (Fig. 2(d)). The thickness is close to the measured value after subtracting the coating layer. The difference in resonance frequency between the experiment and the simulation should be due to the fact that the coating is not considered in the simulation, because of the lack of affirmative property inputs, and its much smaller thickness compared to the silicon coating layer. The difference in resonance frequency between the experiment and the simulation should be due to the fact that the coating is not considered in the simulation, because of the lack of affirmative property inputs, and its much smaller thickness compared to the silicon coating layer.
The magnetic tip has a pyramid shape, and is coated by a layer of hard magnetic CoCr alloy film with a Co:Cr ratio of 80:20. The nominal thickness of the coating is 50 nm. The magnetic properties of the coating layer were evaluated by a vibration sample magnetometer (VSM). Since the tip is too tiny to contribute a detectable signal, we instead measured the magnetization curve of the silicon substrate that holds the tip. As the CoCr alloy was deposited on the silicon substrate and tip simultaneously, we assume that the coatings have the same quality. Figure 2(c) shows the in-plane and out-of-plane magnetization curves which is qualitatively consistent with previous measurements\cite{60, 61}. The results indicate that the easy axis is in the plane and the in-plane hysteresis has a squareness ($M_r/M_s$) of 0.76, so that we would expect that the magnetic moments of the magnetized tip would dominantly stay parallel to the tip surface and point along the applied field direction. The remnant magnetization per area is calculate from the measurement to be $M_{ra} = 0.034$ A, which is used to calculate the exotic forces later.

In order to qualitatively verify the magnetism of the tip, we have used the tip to image a hard-disk plate with magnetic force microscopy (MFM). The hard-disk plate was magnetized to periodic patterns using a home-made magnetic writing device. The period of the pattern is $\sim 10 \mu$m. In the MFM imaging, the topography is measured in the trace scan and then the resonance frequency shift ($\Delta f$) is measured in the retrace scan at a lifted height. Figure 2(e) shows the frequency shift image taken at a lifted height of 150 nm. The period of the image is consistent with the expected value, which qualitatively verify the magnetism of the tip. The images have been taken both before and after the experimental runs, and we observed no significant change between those images.

### B. Nucleon source structure

A periodic structure with alternative high density (gold) and low density (silicon dioxide) materials is used
to provide the source of nucleons. The density modulation structure was fabricated on a silicon wafer topped with a 200 nm thick SiO$_2$ layer. A 190 nm thick gold film was first evaporated on the oxide as a conductive layer, and then another 1.01 µm thick SiO$_2$ layer was deposited on the gold layer by plasma enhanced chemical vapor deposition (PECVD), which serves as the low-density material. Afterwards, the SiO$_2$ layer was patterned to parallel trenches with a period of 20.10 µm using optical lithography and reactive ion etching (RIE). Each trench has a width of 1.00 µm and a depth of 1.01 µm. The trench was then filled with gold by electroplating, which is used as the high nucleon density material. Finally, the structure was glued on a glass substrate, and then the silicon wafer was removed by alkali etching (20 % KOH with addition of hydroxylamine) followed by HF acid etching of the oxide layer. Figure 4 presents a SEM image of the cross section of the nucleon source structure, the dimensions of the structure are listed in Table I. The surface roughness is around 4 nm as measured with atomic force microscopy (AFM), and the averaged periodic corrugation is ~ 2 nm.

### C. Displacement amplitude measurement

The experiment has been performed on a home-built scanning probe microscope as described in ref. [52, 62]. The measurements have been conducted in frequency modulation atomic force microscopy (FM-AFM) mode with constant drive, where the cantilever is excited by a piezo plate with a constant drive amplitude. The drive frequency is tracked to the resonance of the cantilever dynamically with phase-locked loop control. The displacement of the cantilever is measured by a fiber interferometer. Its displacement sensitivity, $S_{int} = dz/dV_{int}$, is obtained through polynomial fitting of the cavity length dependent signal $V_{int}$ near the working point where the cavity length is adjusted to maximize the sensitivity. The displacement amplitude is demodulated with a lock-in amplifier. The noise of the amplitude measurement is evaluated at large tip-sample distance where the tip is supposed to be free of sample’s action. The standard deviation is estimated to be 14 pm for a acquisition time of 60 ms.

### IV. RESULTS AND DISCUSSIONS

#### A. Displacement amplitude imaging

To avoid accidentally recording data in special location, we have taken two dimensional (2D) images at several regions of hundreds micrometer away to check the consistency. The images were taken by scanning the magnetic tip over the source mass at constant tip-sample separation. Both oscillation amplitude and interferometer signal were taken simultaneously. The image size is usually 40 µm × 40 µm (128 × 128 pixels). The fast scan direction is chosen to along the $x$-direction (perpendicular to the stripes). The data acquisition time is 60 ms for every pixel. The sensitivity $S_{int}$ is calculated for every pixel according to its interferometer signal $V_{int}$, which can partially correct the drift of the sensitivity.

Figure 4(a) shows a typical image taken at a tip-surface distance of 500 nm. The oscillation amplitude is around 2.6 nm. In this image, we observe no obvious periodicity related to the density modulation. In order to highlight the signal variation with respect to the density modulation other than a constant or linear background, we subtract the data by its linear fit along the $x$-direction line by line. The result is presented in Fig. 4(b) where random signals are observed with a standard deviation of 14 pm, which is identical to the value obtained at far tip-sample distance. We further average the linearly subtracted data along the y-direction to look for the $x$ dependence of the signal. A simple sine wave fit to the data shows that the amplitude is 0.13±0.17 pm. Such measurements have been performed at four locations laterally separated more than hundreds micrometers away from each other. All images show similar characteristics, and no obvious periodicity has been observed with respect to the density modulation.

The distance dependence of the data can give us important information about the exotic interaction. It is expected that the interaction should decay exponentially with distance. We have performed such measurements at distances of 730 nm, 980 nm, 1294 nm, 1573 nm, 1806 nm. The images taken at different distances exhibit...
similar characteristics, and no obvious periodic patterns can be observed. Except that the data points at larger distances unusually have larger values, the signal is almost independent of distance within the fitting error (see Fig. 5). The larger values may be due to the unstability of the cantilever oscillation for these two data sets. The result implies that no novel exotic interaction is observed in this experiment. We will then derive the constraints on the coupling constant in the following sections using the data taken at the shortest distance.

**B. Exotic force calculation**

In order to extract the coupling constant of the exotic force from the experimental data, the exotic force is calculated by numerical integration. The interaction potential is obtained by integrating all spins over the coating layer of the tip and all the nucleons in the source mass, which is given by

\[
V_{12+13}(x,d) = g_A^e g_V^N \frac{\hbar}{4\pi} \int_{\text{tip}} dS_t \int_{\text{source}} dV_s n(x_s,y_s,z_s) \frac{R_{so} M^* \hat{r} \cdot \hat{v}}{\mu_B r} e^{-r/\lambda},
\]

where \( n(x_s,y_s,z_s) \) is the nucleon number density at \((x_s,y_s,z_s)\) in the source mass, \( r \) is the distance between the spin on the tip and the source mass element, \( \mu_B \) is the Bohr magneton, and \( R_{so} \) is the ratio of spin magnetic moment to the total magnetic moment. The angle \( \theta \) between the cantilever and the source surface is considered in the calculation. The potential is a function of the relative lateral position \( x \) and distance \( d \) between the tip and the source mass. By taking derivative of Eq. (4) with respect to \( d \), the \( z \) component of the exotic force is derived. The \( R_{so} \) is determined to be 0.92 according to the spin-polarized density functional theory (DFT) calculation of the CoCr alloy (see details in Appendix. A). An example of the expected force signal is shown in Fig. 1(b), and we can see that the force is periodic with respect to the relative position \( x \).

**C. Spurious forces**

The exotic force depends on the relative velocity, so that the higher oscillation frequency, the greater the expected signal. That is why we chose a stiffer cantilever with a higher resonance frequency. At such high frequency, the vibration noise of the environments is extremely small. For the spurious forces, such as the Casimir force, electrostatic force and magnetic force, they are all independent of the relative velocity. They affect the oscillation amplitude of the cantilever by introducing an extra effective spring constant equal to the force gradient \( k_{ts} = -\partial F_{ts}/\partial z \) between the tip and source mass.

We calculated the Casimir force and electrostatic force by using the proximity force approximation\[63\]. At a tipsurface distance of 500 nm, the Casimir force gradient is estimated to be \( 2.5 \times 10^{-9} \) N/m, and the electrostatic force gradient is estimated to be \( 2.0 \times 10^{-10} \) N/m with 5 mV residual potential difference between the tip and source mass. Their impact on the oscillation amplitude is less than \( 10^{-8} \) nm, which is negligible compared to the noise floor of the amplitude measurement. The normal magnetic force between the magnetic tip and the source mass is evaluated with finite element simulation. In order to calculate the tiny force, the source mass is simulated as
and total experimental uncertainty at pixel \((i,j)\) and \(\sigma\) the 2
described in section IV B. Here, we conservatively use
be larger. The
table values in the calculation, so that the real value should
only spins in the dashed rectangle marked in Fig. 2(a)
calculate the theoretical values. It should be noted that
which is also negligible in this experiment. Therefore,
the influence of the above forces can be ignored thanks
to the velocity dependence of the exotic force and the
resonance detection scheme.

D. Constraints on the coupling constant

To set constraints on the coupling strength of the ex-
otic interaction, we analyze the images with maximum
likelihood estimation. The probability density of observ-
ing the image is calculated as a function of the position
offset \(x_0\) and the coupling strength \(f_v = 2g_A g_N^N\) for every
\(\lambda\) according to

\[
P(x_0, f_v, \lambda) = \frac{1}{A} \prod_i \frac{1}{\sqrt{2\pi} \sigma_{ij}} e^{-\left( f_{ij}^{\exp} - f_{ij}^T(f_v, \lambda) \right)^2 / 2\sigma_{ij}^2},
\]

where \(A\) is the normalization coefficient, \(f_{ij}^{\exp}\), \(f_{ij}^T(f_v, \lambda)\)
and \(\sigma_{ij}\) are the experimental data, theoretical value,
and total experimental uncertainty at pixel \((i,j)\), respectively.

The exotic force per unite velocity \(f_{ij}^{\exp}\) is calculated as
described in section IV B. Here, we conservatively use
the 2\(\sigma\) bound values of the experimental parameters to
calculate the theoretical values. It should be noted that
only spins in the dashed rectangle marked in Fig. 2(a)
are used in the calculation, so that the real value should
be larger. The \(f_{ij}^{\exp}\) is the experimental data at pixel
\((i,j)\), converted from the oscillation amplitude image by
eq. \(\text{Eq. } 5\). The experimental uncertainty of \(f_{ij}^{\exp}\) is the
quadarure sum of the errors contributed from \(k\), \(Q\), \(\omega_0\),
\(z_{far}\) and \(z_{\text{amp}}(i,j)\). The parameters \(\omega_0\), \(Q\) and \(z_{far}\) were
measured at far distance where the cantilever is assumed
to vibrate freely. The mean values and uncertainties of
those parameters are list in Table I. The uncertainty of
amplitude measurement \(\delta z_{\text{amp}}\) is set to 14 pm as evalu-
ated independently at far distance. An example of the
probability density function is shown in Fig. 6.

The probability as a function of \(f_v\) is obtained by in-
tegrating out the \(x_0\), and the up-bound of \(f_v\) at 95% con-
fidencial level can be derived for every \(\lambda\). The result,
based on the data taken at 730 nm distance, is pre-
sented in Fig. 7 together with other experimental con-
strains reported previously. The atomic magnetometer
experiment constrains the exotic force above 180 \(\mu m\) \(5\).\(\phi\). For
the interaction range below 2.3 \(\mu m\), the limits are set by comparing the atomic PNC experimental result
and theoretical calculations \(18\). This work sets stronger
constraints than the PNC experiment at the interaction
range from 2.3 \(\mu m\) to 180 \(\mu m\). We noticed that a recent
experiment using a single-electron spin quantum sensor

FIG. 5. Distance dependence of the signal obtained by fitting
the 2D images to the sine wave surface function \(z(x, y) =
\text{Asin}[2\pi(x-x_0)/\Lambda]\), where \(\Lambda\) is the density modulation period.

FIG. 6. (a) Normalized probability density as a function of \(x_0\)
and \(f_v\) for \(\lambda = 1 \mu m\) . (b) Normalized probability density as a
function of \(f_v\) by intergrating out \(x_0\).The curve is fitted to the
Gaussian function,which gives \(f_v = 3.3 \times 10^{-16} \pm 3.6 \times 10^{-13}\)
at 95% confidential level.
By assuming a limit on $g_A^N$ from this work as well as previous experiments [65, 66], even stringent constraints may be obtained by the combination of $g_A$ and $g_N^v$ as explained in the main text.

reported a stronger limit in this range [64]. Even stringent constraints may be obtained by the combination of $g_A$ and $g_N^v$ from different experiments. We derive the limit on $(g_A^N)^2$ from the spin-spin experiments [42, 44]. By assuming $g_A^N = 0$, the limit on $(g_A^N)^2$ can be obtained from the non-Newtonian gravity experiments [66, 68]. Finally, we obtain the limit on the combination $g_A^* g_N^*$, as shown by the dashed line in Fig. 7. Nevertheless, direct experimental search with fewer assumptions are still worthwhile.

V. CONCLUSIONS

In conclusion, we have performed an experimental search for the exotic parity-odd spin- and velocity-dependent interaction with a magnetic force microscope. The magnetic probe is taken as a source of the moving spin polarized electrons and also the force sensor to measure the exotic interaction. The magnetic properties of the tip is evaluated quantitatively by VSM and qualitatively by MFM measurement on a hard-disk plate. The density modulation source mass is adopted to generate a periodic signal, so that we are able to extract the exotic interaction from non-periodic background. We obtain the coupling constant by using maximum likelihood estimation, and observe no new interaction above the experimental sensitivity. The experiment sets constraints on the coupling constant between spin polarized electrons and unpolarized nucleons at the micrometer range using a direct force measurement method. Future improvements could be achieved by replacing the magnetic tip with a spherical magnet. The spherical magnet of micrometer size can be magnetized to single domain due to its symmetry and could provide more spins to interact with the source mass.

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Appendix A: Density functional theory calculation

The spin-polarized DFT calculations are performed by using the Vienna Ab Initio Simulation Package (VASP) code [67]. Perdew-Burke-Ernzerhof (PBE) functional is employed to describe the exchange correlation interactions within the generalized gradient approximation. The electron-ion interactions are represented by the projector augmented wave (PAW) method [68, 69]. The energy cutoff of plane wave is set to be 500 eV and the convergence criterion for the residual forces and total energies are set to be 0.01 eV/Å and 10^{-6} eV, respectively. The primitive cell with two Co atoms, a 2x2x1 supercell with 6 Co and 2 Cr atoms, and a 2x2x2 supercell with 13 Co and 3 Cr atoms are constructed to calculate the spin and orbital magnetic moment of hcp-Co, hcp-Co$_3$Cr and hcp-Co$_5$Cr$_3$ alloy, respectively. The $\Gamma$-centered 9x9x6, 5x5x6 and 5x5x2 Monkhorst-Pack k-point mesh are used to sample the Brillouin zones of hcp-Co, hcp-Co$_3$Cr and hcp-Co$_5$Cr$_3$ alloy, respectively. The $R_{so}$ values are found to be 0.96, 0.93, 0.90 for pure Co, Co$_5$Cr$_3$ and Co$_3$Cr, respectively. The value decreases with increasing the concentration of Cr. By interpolating the data, we estimate the $R_{so}$ value for Co$_{50}$Cr$_{20}$ to be 0.92.

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