New Constraints on Exotic Spin-Dependent Interactions with an Ensemble-NV-Diamond Magnetometer

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Abstract

Laboratory search of exotic interactions is crucial for exploring physics beyond the Standard Model. We report new experimental constraints on two exotic spin-dependent interactions at the micrometer scale based on ensembles of nitrogen-vacancy (NV) centers in diamond. A thin layer of NV electronic spin ensembles is synthesized as the solid-state spin quantum sensor, and a lead sphere is taken as the interacting nucleon source. Our result establishes new bounds for two types of exotic spin interactions at the micrometer scale. For an exotic parity-odd spin- and velocity-dependent interaction, improved bounds are set within the force range from 5 to 500 μm. The upper limit of the corresponding coupling constant $g_A^e g_V^N$ at 330 μm is more than 1000-fold more stringent than the previous constraint. For the *P,T*-violating scalar-pseudoscalar nucleon-electron interaction, improved constraints are established within the force range from 6 to 45 μm. The limit of the corresponding coupling constant $g_S^N g_P^e$ is improved by more than one order of magnitude at 30 μm. This work demonstrates that a solid-state NV ensemble can be a powerful platform for probing exotic spin-dependent interactions.

Introduction

Experimental search of interactions beyond the standard model (SM) has attracted broad interest in recent years[1]. Numerous theoretical models indicate long-range interactions beyond the SM that can be mediated by new bosons, such as axions and dark photons. The exchange of hypothetical particles gives rise to exotic spin-dependent interactions between fermions, which were first proposed by Moody and Wilczek in 1984[2]. In this work, we focus on searching for two types of exotic interactions between electron spin and nucleon, which can be described as[3]

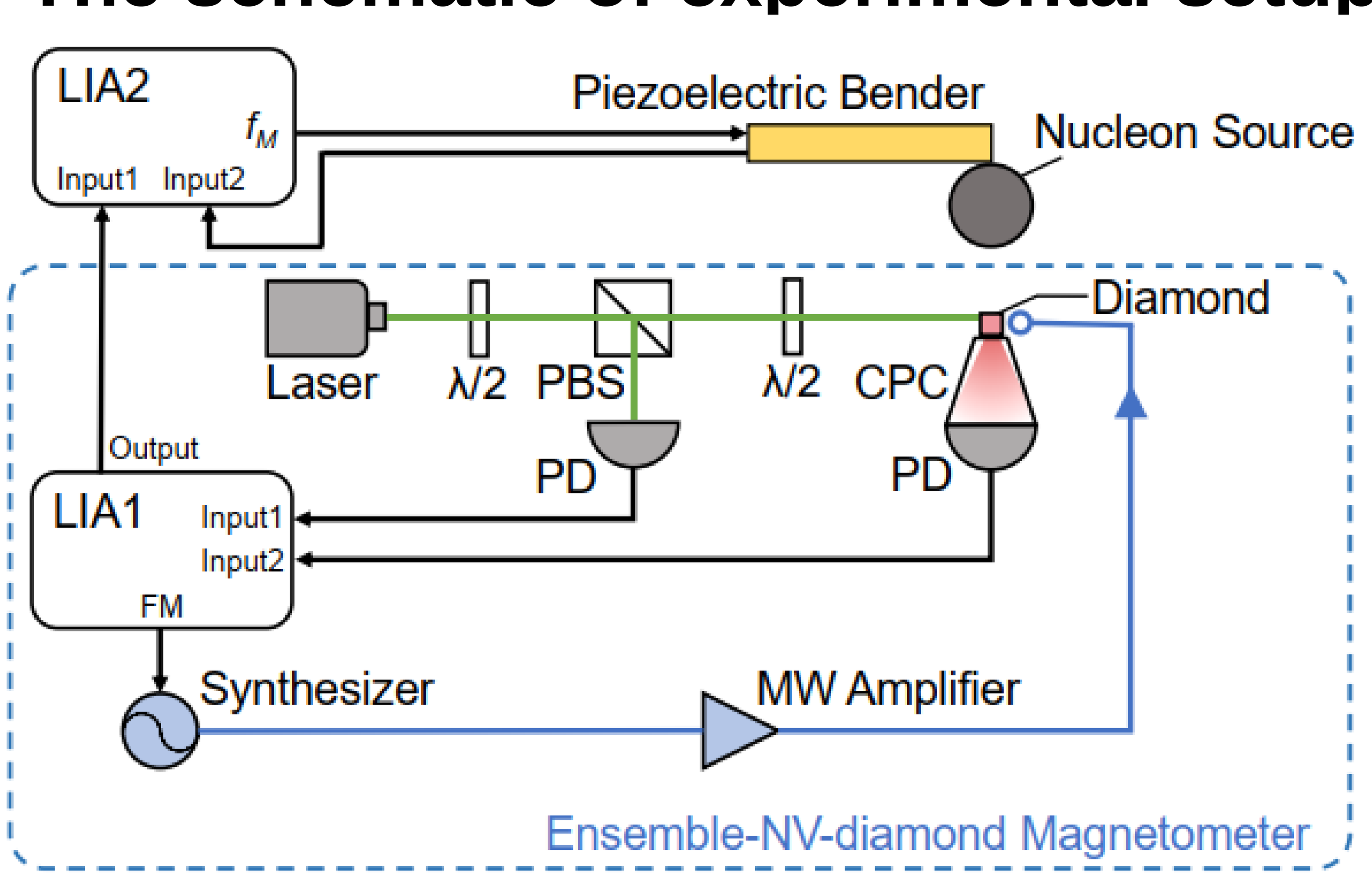
$$V_{\mathrm{AV}} = g_A^e g_V^N \frac{\hbar}{4\pi}\left(\frac{e^{-r/\lambda}}{r}\right)\hat{\sigma}_1 \cdot \vec{v}$$

$$V_{SP} = g_S^N g_P^e \frac{\hbar^2}{8\pi m_e}\left(\frac{1}{\lambda r}+\frac{1}{r^2}\right)e^{-r/\lambda}(\hat{\sigma}_1 \cdot \hat{e_r})$$

The interactions induce effective magnetic fields B_{AV} and B_{SP}, which can be measured by our Ensemble-NV-Diamond Magnetometer.

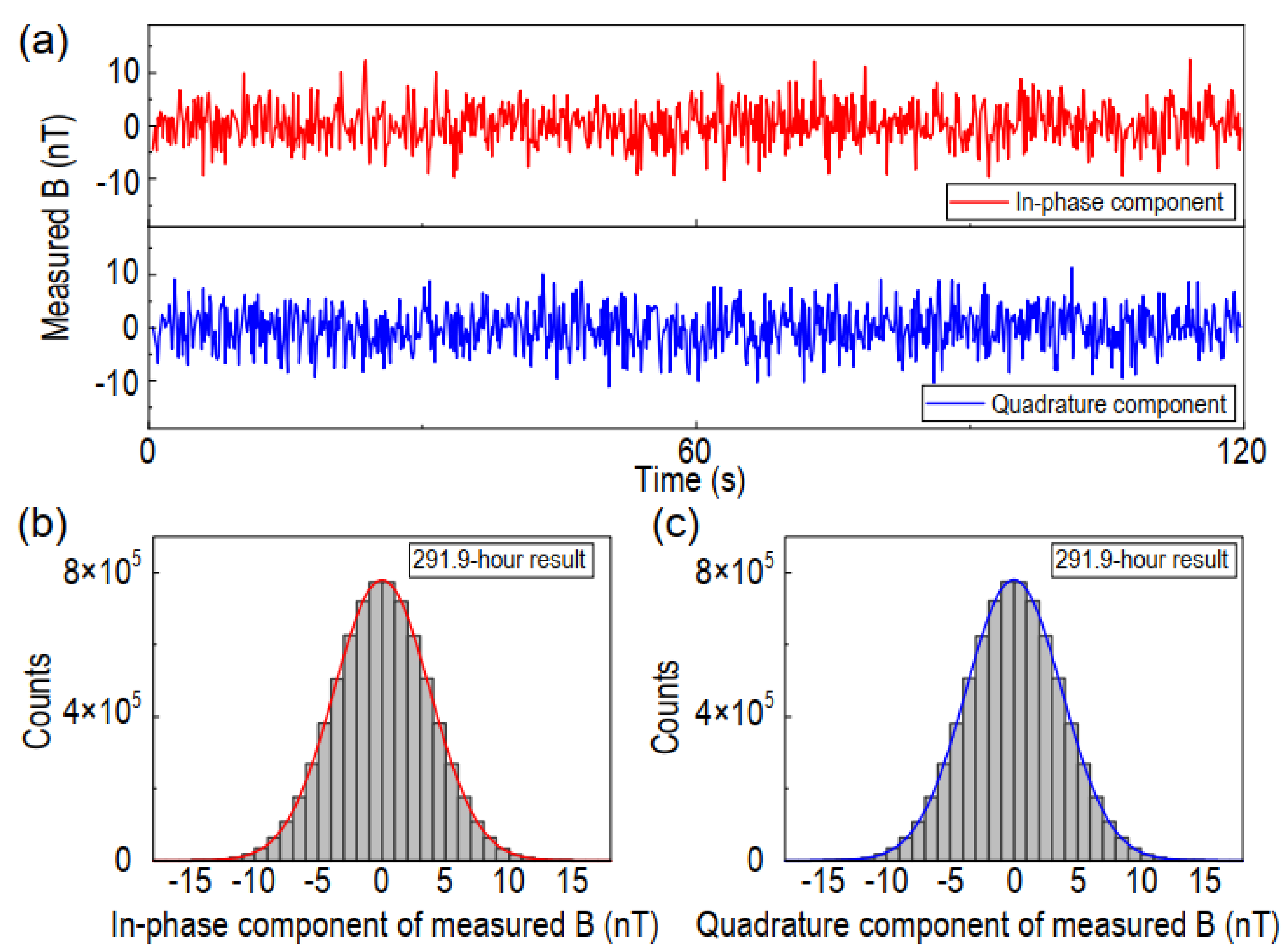
[1] M. S. Safronava, *et al.* Search for new physics with atoms and molecules. Rev. Mod. Phys.90,025008 (2018).
[2] J. E. Moody and Frank Wilczek. New macroscopic forces? Phys. Rev. D 30, 130 (1984).
[3] Bogdan A. Dobrescu and Irina Mocioiu. Spin-dependent macroscopic forces from new particle exchange. JHEP11(2006)005.

The schematic of experimental setup



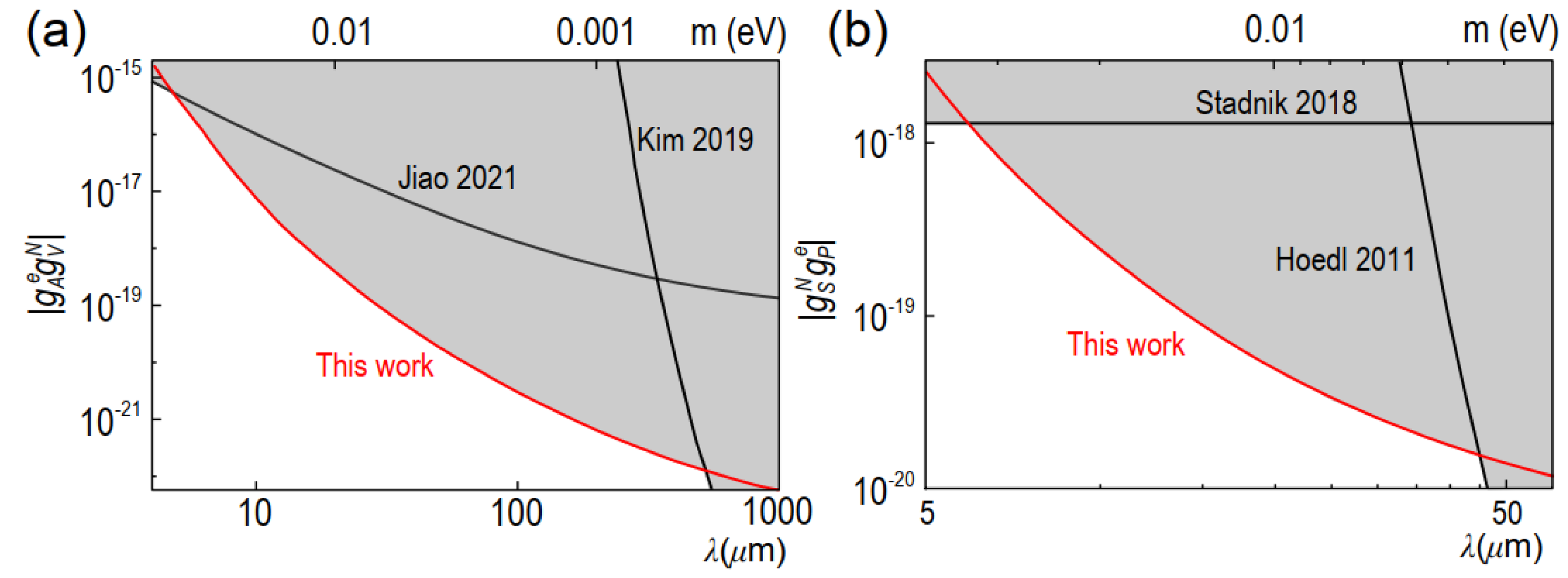
Experimental setup based on an ensemble-NV-diamond magnetometer. A high-purity lead sphere with a radius of R = 978(3) μm was taken as the nucleon source. The lead sphere was attached to a piezoelectric bender, which can vibrate at a frequency f_M = 1.953 kHz. The sensor is an ensemble of NV centers in a 23-μm-thick layer at the surface of the diamond. A 532-nm laser with a diameter of 0.8 mm illuminated the NV doped layer via the flank of the diamond. The red fluorescence from the NV centers was collected by a compound parabolic concentrator(CPC), filtered by a long-pass filter, and detected by a photodetector (PD). The frequency of microwave from the synthesizer was modulated with a frequency FM being 87.975 kHz using LIA1, and the output of the LIA1 was then demodulated by the second lock-in amplifier (LIA2) with a frequency f_M = 1.953 kHz.

Experimental results



Measurement results of the two effective magnetic fields. (a) The red (blue) line corresponds to B_{SP} (B_{AV}) with the time duration being 120 seconds, which is from the in-phase (quadrature) component of the output of the second lock-in amplifier. (b) and (c) The histograms of experimental results for 291.9-hour data. The red and blue solid lines are fits to the Gaussian distributions. The averages and the standard errors of the B_{SP} and B_{AV} are (-1.3 $\pm$1.4) pT and (0.1 $\pm$ 1.4) pT, respectively.

New experimental constraints



New experimental constraints are established. (a) Upper limits on $g_A^e g_V^N$, as a function of the force range λ and mass of the bosons m. Black lines are upper limits established by previous experiments. The red line is the upper bound obtained from our experiment, which establishes an improved laboratory bound in the force range from 5 to 500 μm. (b) Upper limits on $g_S^N g_P^e$. Black lines are upper limits established by previous experiments. Our experiment set the most stringent constraints in the force range from 6 to 45 μm.