A spin-mechanical quantum chip for exploration of submicron exotic interactions

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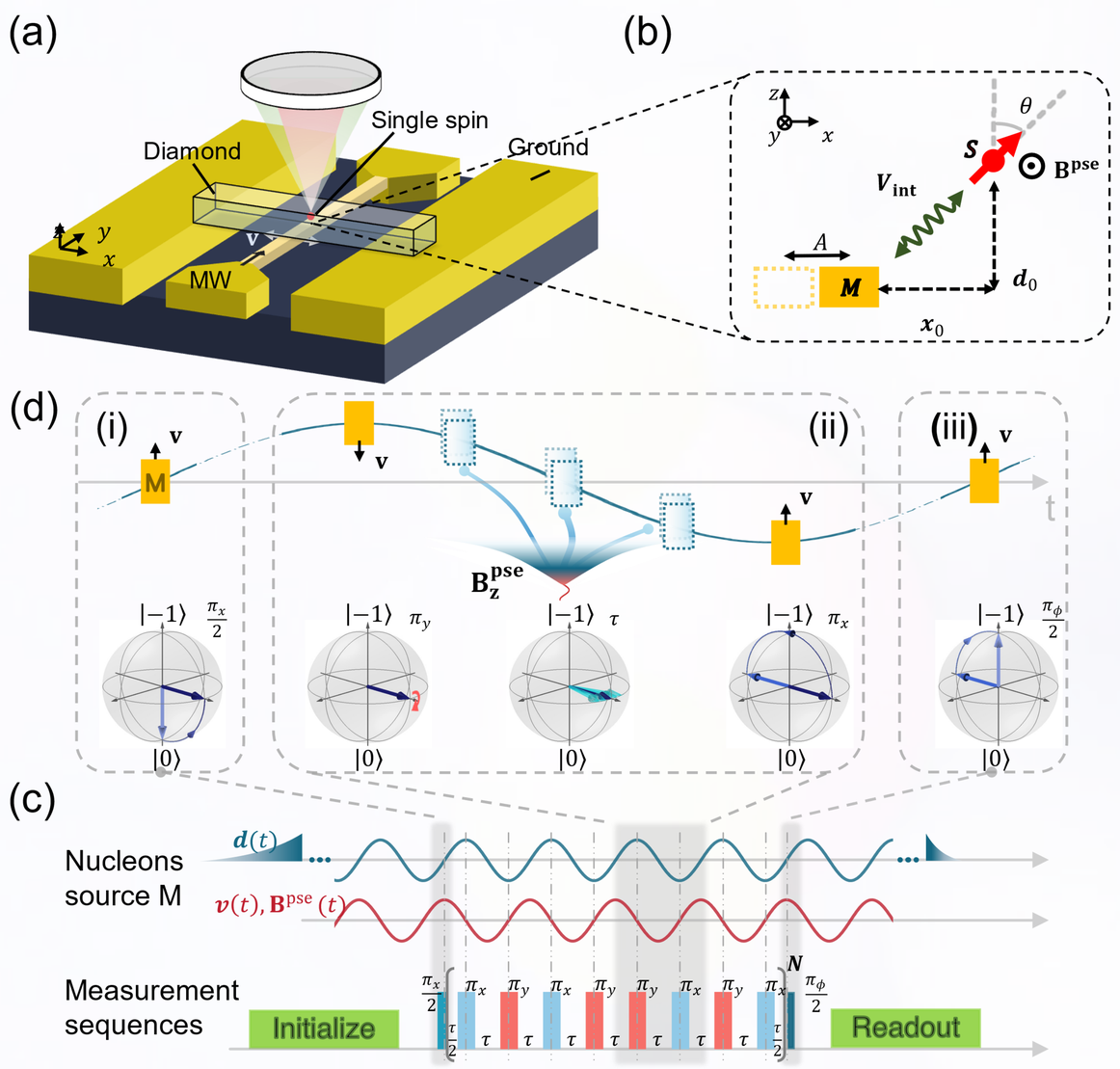
Abstract

How to illuminate dark matter has become the foremost open question in fundamental science nowadays and has great significance in understanding the laws of nature[1, 2]. In the past decades, a variety of laboratory-scale and tabletop-scale setups have emerged as complementary methods in searching for a series of predicted low-mass bosons, such as axions and axion-like particles (ALPs)[3]. However, the frontiers of new bosons–the beyond-the-Standard-Model interactions they mediate–known as the so-called "fifth" forces[4], can also be explored at nanoscale with more compact devices.

Here, we report an on-chip detector used to search for the hypothetical spin-velocity dependent interactions, by placing a micro-scale diamond with single Nitrogen-Vacancy (NV) spins above a micro-mechanical resonator. We find under our experimental sensitivity no evidence for the existence of new bosons in the force range **below 100 nm**, i.e., in the bosons rest-mass window of 2–10 electronvolts. The constraint is improved by two orders of magnitude. Furthermore, based on the proof-of-principle experiment, we propose a promising chip integrated with a large number of detectors working together. This work marks the milestone of new interaction searching into nanoscale region, with low-cost and scalable quantum chips.

Spin-mechanical quantum chip



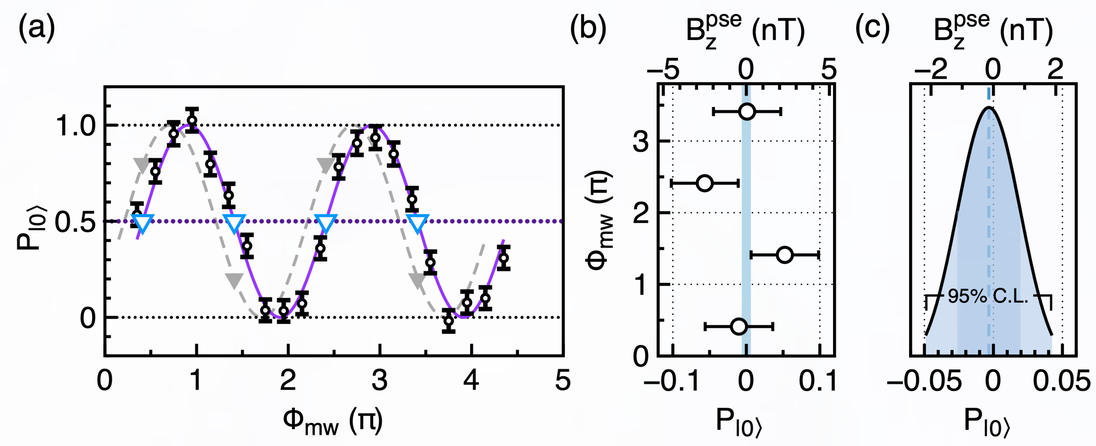
A hypothetical new-bosons-mediated spin- and velocity-dependent interaction between a polarized spin and moving unpolarized nucleons

$$\mathcal{V}_{\rm int}(r) = -f^{\perp}\frac{\hbar^2}{8\pi m_e c}[\hat{\sigma}\cdot(\mathbf{v}\times\mathbf{r})]\left(\frac{1}{\lambda r}+\frac{1}{r^2}\right)e^{-\frac{r}{\lambda}}$$

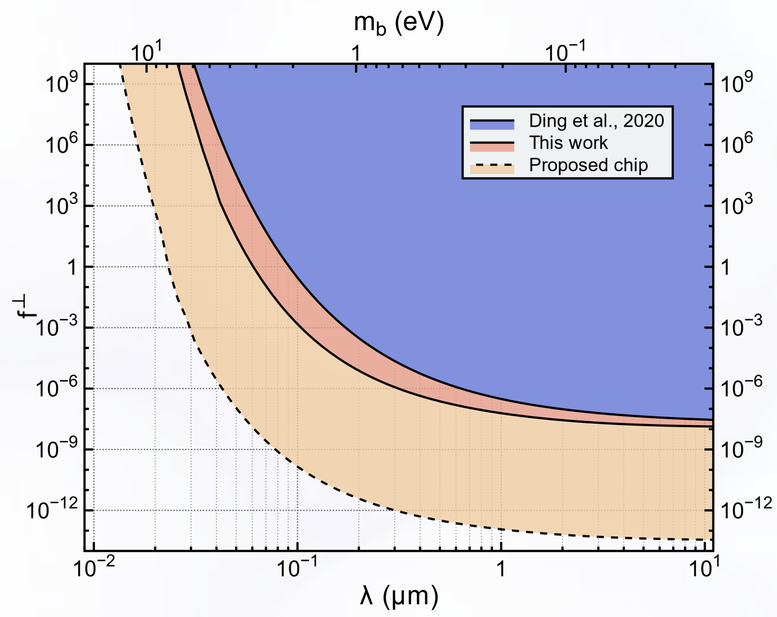
the hypothetical interaction $\mathcal{V}_{\rm int}$ is regarded as $\gamma\hbar/2(\hat{\sigma}\cdot\boldsymbol{B}^{\rm pse})$, which induces a weak pseudo magnetic field applied on the single electron spin of NV center.

Testing sub-μm exotic interactions on-chip. (a) Schematic of the detector. With 50 nm-depth single NV centers (red dot) on the lower surface, a micro-scale diamond is positioned above a horizontally oscillating beam. The single spin (the electron spin in NV centers) is excited and read through the 532 nm green laser and red fluorescence, respectively (green squares in (c)). The microwave (MW) applied through the coated gold layer on the beam is used to manipulate the single spin. (b)Schematic of the principle: The exotic spin- and velocity-dependent interaction $\mathcal{V}_{\rm int}$ from the nucleons source element M will induce a pseudo vector magnetic field $B^{\rm pse}$ applied on the single spin S. The integral $B^{\rm pse}$ is affected by the velocity of M and the relative location between M and S. (c) N times repeated XY8 pulse sequences is used for sensing the pseudo magnetic signal. The middle of π-pulses is aligned with extreme points of M's displacement (blue line), that is, the maximum of M's velocity (red line). The interval between π-pulses is $\tau = (\pi/\omega_{\rm d} - t_\pi)$. (d)Diagram of measurement shown with a Bloch sphere. (i)The $\pi_x/2$-pulse rotates the spin state from its pole $|0\rangle$ to XY-plane (superposition state of $|0\rangle$ and $|-1\rangle$). (ii) The pseudo magnetic field $B_z^{\rm pse}$ causes the spin rotating in XY-plane during each free evolution interval τ, resulting a shifted phase in $|-1\rangle$. The spin is flipped every time the moving direction of M changed, so that the phase shift in the plane will accumulate all the time rather than cancelled. (iii) The $\pi_\varphi/2$-pulse rotates the spin state to convert the accumulated phase into population difference of $|0\rangle$ and $|-1\rangle$.

Results of experimental searches



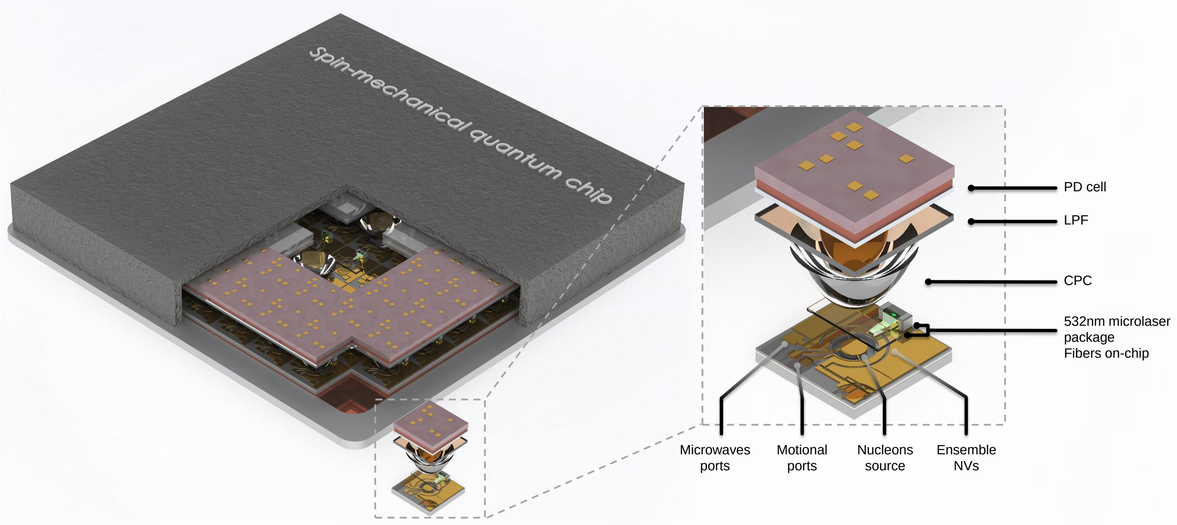
Experimental results for testing the parity-even spin- and velocity-dependent interaction. (a) Normalized population of state $|m_s = 0\rangle$ variation with $\varphi_{\rm mw}$, measured by XY8-8 sequence. Each point (circle) is the average of 20 million experimental trails, fitted by the purple line. The blue triangles mark the maximum sensitive points for pseudo magnetic field sensing. The gray dashed line and triangles show how the $P_{|0\rangle}$ trends if a hypothetical magnetic field is applied. (b) Difference between the signals with M driven or not, $P_{|0\rangle}^{\rm on} - P_{|0\rangle}^{\rm off}$, each point is the average of 60 million experimental trails. (c) Statistical analysis for measured pseudo magnetic field. $B_z^{\rm pse} = -0.146 \pm 2.026\,\mathrm{nT}$ is obtained from the population results. The significant deviation **0.144σ** from zero is achieved, indicating that none exotic interaction is observed. The deep blue gray region shows the 90% C.L. region, and the light blue gray region shows the 95% one.



Constraints for searching unexplored bosons. Upper limits on the exotic-even spin- and velocity-dependent interaction as a function of the force range λ and mass $m_{\rm b}$.

- Purple areas: experiments in Ding et al., 2020.
- Red areas: this work [2 orders of magnitude under 0.1μm force range].
- Dash lines with Orange areas: Prospect of integrated CPU-scale chip at difference gap distances [0.6μm], achieves around 6-order improvements of magnitude better.

Futural spin-mechanical quantum chip



Prospect of spin-mechanical quantum chip. The chip is integrated with numbers of spin-mechanical unit for detection of exotic interactions. Each **unit [$500\mu m^3$]** is independent with each others during working.

- Nucleons source: a thin disk coated with gold is suspended and manipulated through two motional ports by capacitive coupling.
- Spins: a ensemble NVs diamond is placed above and manipulated through two microwaves ports which form a Ω-structure for homogeneous controls.
- Gap controls: thicknesses of the ground or four piers on the diamond.
- ODMR system [all-optical processing on one chip]: a 532nm microlaser is installed and the light is guided through fibers to the diamond. The fluorescence from NVs is collected more efficient by a compound parabolic concentrator (CPC) into the upper chip which is made of a long-pass filter (LPF) and photon detection (PD) cell. The CPC also works as a support between chips.

Reference

* L. Wu, and S. Lin contributed equally to this work.

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