Search for axion-like dark matter with spin-based amplifiers

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Ultralight axion-like particles are well-motivated dark matter candidates introduced by theories beyond the standard model of particle physics. However, directly constraining their parameter space with laboratory experiments usually yields weaker limits than indirect approaches relying on astrophysical observations. Here we report the search for axion-like particles with a quantum sensor in the mass range of 8.3–744.0 eV. The sensor makes use of hyperpolarized long-lived nuclear spins as a pre-amplifier that effectively enhances a coherently oscillating axion-like dark matter field by a factor of more than 100. Using these spin-based amplifiers, we achieve an ultrahigh magnetic sensitivity of $18 \text{ fT Hz}^{-1/2}$, which exceeds the performance of state-of-the-art nuclear spin magnetometers. Our experiment constrains the parameter space describing the coupling of axion-like particles to nucleons over the aforementioned mass range, namely, at 67.5 eV reaching $2.9 \times 10^{-14} \text{ GeV}^{-1}$, improving on previous laboratory constraints by at least five orders of magnitude. Our measurements also constrain the quadratic interaction between axion-like particles and nucleons as well as interactions between dark photons and nucleons, exceeding bounds from astrophysical observations.

Despite astrophysical evidence for the existence of dark matter, direct detection of its interaction with particles and fields of the standard model has not been achieved. Illuminating dark matter is the best hope of making progress in understanding our universe and would provide insights into astrophysics, cosmology and physics beyond the standard model. There is a variety of particle candidates for dark matter. Weakly interacting massive particles (WIMPs) have attracted the most attention over the past four decades. Despite many experiments of increasing sensitivity, there are no undisputed signatures of WIMP existence, and fundamental background from the neutrino floor will soon limit the search sensitivity of WIMPs. The axion, emerging from a solution to the strong charge parity (CP) problem, is another well-motivated dark matter candidate. Since the original concept of axion was proposed, axions and other light pseudoscalar bosons (collectively referred to as axion-like particles (ALPs)) naturally emerge when global symmetry is broken at a higher-energy scale, for example, in the grand unified theory, string theory and models with extra dimensions.

Traditional particle-physics techniques such as the observation of particle collisions are completely inadequate for ALP searches with light quanta. Experimental searches for axion-like dark matter are based on their non-gravitational interactions with particles and fields of the standard model, where ALPs act as a time-oscillating magnetic field that couples to nuclear spins. Experiments with nuclear magnetic resonance (NMR) techniques directly search for axion–nucleon interactions, where ALPs act as a pre-amplifier to greatly amplify the signal from coherently oscillating ALP dark matter field by a factor of more than 100. Then, the amplified ALP signal can be searched with a conventional atomic magnetometer. We would like to emphasize the difference in ALP search approaches between this work and other studies. Resonant NMR searches for ALPs have been proposed, and their experimental demonstrations are ongoing. Such works consider the situation in which nuclear spins are measured from their proximity with atomic and superconducting quantum interference device magnetometers; in this case, it is experimentally challenging to prepare nuclear spins with high spin polarization and maintain the readout sensitivity. Unlike previous works, our work uses a different scheme which couples multiple resonators and sic to nuclear spins, where spin signals can be enhanced due to large Fermi-contact enhancement factor, detected in situ with an atomic magnetometer. For a heavy noble gas, such as $^{129}$Xe, the magnetic field generated by

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nuclear magnetization can be enhanced by a large factor of 540. In this way, we realize the spin-based amplification of ALP signals and immediately achieve high sensitivity to ALPs.

Axion-like particles could have been produced in the early Universe by non-thermal mechanisms, such as vacuum misalignment.\(^4\) They form a classical field \(a \approx a_0 \cos(2\pi \nu t)\) (refs. 23,25–29), oscillating at its Compton frequency \(\nu_c = m_c^2 / h\), where \(m_c\) is the axion mass, \(c\) is the speed of light and \(h\) is the Planck constant. In the standard halo model, the characteristic coherence time of this oscillating ALP field is \(\sim 10^9\) periods. The field amplitude \(a_0\) can be estimated by the Galactic dark-matter energy density \(\rho_c = m_c^2 a_0^2 / (2h^2) \approx 0.4\) GeV cm\(^{-3}\) (refs. 9,41). ALPs would interact with nuclear spins by a Zeeman-like Hamiltonian \(H_{\text{Z}} \approx \gamma B_\text{eff} I_\text{z}\), where \(B_{\text{eff}} = g_{\text{NN}} \sqrt{2\hbar c} \gamma_0 \langle 2\nu_{\text{ALP}} \rangle / y\) represents the effective magnetic field induced by ALP dark matter (Supplementary Section IV) and \(I_\text{z}\) is the nuclear spin. Here \(g_{\text{NN}}\) is the strength of the axion–nucleon coupling, which uses the same definition used in refs. 23,30, and has the unit of GeV\(^{-1}\). Also, \(|y| \approx 10^{-8}\) represents the local Galactic virial velocity\(^25\) and \(y\) is the gyromagnetic ratio of nuclear spin. Our ALP search scheme is based on detecting the effective \(B_{\text{eff}}\) and measuring or constraining the strength \(g_{\text{NN}}\) over a range of ALP masses.

Our approach involves the use of hyperpolarized \(^{129}\)Xe gas as a spin-based amplifier. Here \(^{129}\)Xe spatially overlaps with \(^{87}\)Rb in the same vapour cell, where nuclear spins of \(^{129}\)Xe act as an ALP pre-amplifier and \(^{87}\)Rb magnetometer further reads the amplified ALP signal. When the ALP Compton frequency \((\nu_c)\) matches the \(^{129}\)Xe Larmor frequency \((\nu_L \approx \gamma B_{\text{eff}})\), that is, \(\nu_c \approx \nu_L\), ALPs tilt the \(^{129}\)Xe spins away from the direction of the applied bias magnetic field, as shown in Fig. 1a. Subsequently, the detection signature of ALP dark matter is an oscillating nuclear transverse magnetization \(M_{\text{z}}(t)\) (Supplementary Section II). The pre-amplified effective field experienced by the \(^{87}\)Rb atoms is given by \(B_{\text{eff}} = (8\pi c/3) M_{\text{z}}\) (refs. 24,41). Due to the large Fermi-contact enhancement factor \(\kappa_{\text{c}} \approx 540\) between \(87\)Rb and \(^{129}\)Xe, the effective field \(B_{\text{eff}}\) can be significantly larger than the ALP field \((|B_{\text{eff}}| \gg |B_{\text{eff}}|)\). This allows us to achieve considerable amplitude amplification of the ALP signal and thereby improve sensitivity to ALP dark matter. In contrast, when the ALP frequency is different from the Larmor frequency, there is no measurable transverse magnetization \(M_{\text{z}}(t)\) and therefore \(B_{\text{eff}} \approx 0\) (Fig. 1b). The effective field \(B_{\text{eff}}\) can be read out in situ by a sensitive \(^{87}\)Rb magnetometer (Fig. 1c).

We experimentally measure the amplification of the signal from the ALP field by applying a weak oscillating magnetic field to simulate an ALP field. The amplification factor is defined as \(\eta = |B_{\text{eff}}| / |B_{\text{eff}}|\). For example, the bias field is set at \(B_0 \approx 759\) nT, corresponding to \(\nu_L \approx 8.96\) Hz. A simulated ALP oscillating field with an amplitude of \(\sim 30\) nT and frequency of 8.96 or 8.30 Hz is applied to the vapour cell along \(y\). We collect 100 s of data and then perform a discrete Fourier transform on the acquired data. As shown in Fig. 2a (top), the signal is greatly enhanced when the applied oscillating-field frequency coincides with the \(^{129}\)Xe Larmor frequency. This is in contrast to the
Fig. 2 | Proof-of-principle demonstrations of the spin-based amplifier. a, Amplification performance of the $^{129}$Xe-spin-based amplifier for on-resonance (top) and near-resonance (bottom) scenarios. The fast Fourier transform spectra for $\nu = 8.96$ Hz (resonance case; top) and $\nu = 8.30$ Hz (near-resonance case; bottom). b, Linear response signals (on-resonance, red circles; far-off-resonance, blue circles) as a function of the oscillating-field amplitude from 15 to 45 pT. The on-resonance slope $\Gamma_{\text{on}} \approx 0.319 \pm 0.002 \mu V$ pT$^{-1}$ is at least two orders of magnitude greater than the far-off-resonance slope $\Gamma_{\text{far}} \approx 2.5 \pm 0.1 \mu V$ pT$^{-1}$. c, Amplification factor $\eta$ as a function of resonance frequency (corresponding to different applied bias fields). Experimental data shown in red circles yield mean $\eta = 128.0 \pm 0.3$. d, Nonlinear responses as a function of the oscillating-field amplitude over a large region (below 70 nT). In the near-zero-amplitude regime, the response of the spin-based amplifier is linear, corresponding to the case shown in (b). In the experiments shown in (a, b) and (d), the bias field is set at $B \approx 759 \text{nT}$, corresponding to $^{129}$Xe Larmor frequency $\omega_L \approx 8.96$ Hz. The black lines are theoretical fits (Supplementary Section II).

When increasing the amplitude of the oscillating fields, we find that the response of the spin-based amplifier to oscillating fields becomes nonlinear. Figure 2d provides the experimental nonlinear response signals, scanned as a function of the oscillating-field amplitude. In contrast to the far-off-resonant cases (7 and 320 Hz), the signals for the resonant (8.96 Hz) and near-resonant (8.80 and 9.05 Hz) cases first increase, then decrease, and finally increase again, which can be attributed to nuclear magnetization saturation. The solid curves shown in Fig. 2d represent our theoretical calculations (Supplementary Section II), which agree well with the experiment. A particularly sensitive window for measuring external oscillating fields corresponds to the amplitude of oscillating fields below several nanoteslas ($B_0 \ll \frac{2}{\gamma^2 T_1 T_2}$), where $T_1$ and $T_2$ denote the longitudinal and transverse spin relaxation times, respectively; see Supplementary Equation 12). In practice, we are interested in a sensitive measurement of small magnetic fields (for example, axion-like dark matter field), whose amplitudes are naturally within the sensitive window demonstrated in this work. To maintain our ALP search in the sensitive window, we carefully suppress the ambient electromagnetic interference, for example, by using a five-layer magnetic shield and an ultralow-noise current source. We present a detailed analysis of the long-term stability of the spin-based amplifier in Supplementary Section III.

Having established the sensing technique, we now quantify the detection sensitivity of our experiment to an ALP dark matter signal. We first calibrate the frequency dependence of our sensor by scanning the frequencies of the oscillating fields and recording the corresponding amplification factor. For example, in a bias field of 759 nT, sensor amplification $\eta$ is illustrated in a small frequency range around the resonant frequency ($\nu \approx 8.96$ Hz). It reaches the maximum value on resonance (Fig. 3a); the frequency dependence of the response is consistent with a single-pole band-pass filter model with a full-width at half-maximum of 0.052 Hz (Supplementary Fig. 7), which corresponds to axion mass of 0.22 feV. Using such a
spin-based amplifier that enhances the measured oscillating field, we achieve a magnetic sensitivity of 18 fT Hz$^{-1/2}$ at the resonance frequency (Fig. 3b), whereas the sensitivity of the$^{87}$Rb magnetometer is only about 2 pT Hz$^{-1/2}$. Calibrated sensitivities with the spin-based amplifier from 2 to 180 Hz are presented in Supplementary Section V. The experiment showcases the capability of our sensor to surpass the photon-shot-noise limit of the rubidium magnetometer itself, approaching the spin-projection-noise limit of the latter. Moreover, our sensing technique is significantly better than that of other state-of-the-art magnetometers demonstrated with nuclear spins, which are limited to sensitivity of a few picoteslas.

We perform the search for ALP signals in the frequency range from 2 to 180 Hz, corresponding to ALP masses ranging from 8.3 to 744.0 feV. In each run, we set a fixed bias field, thus setting the ALP search frequency; further, we record 100 s of signal data. We model the histogram of the power spectral values in the 2 Hz bin centred at $f_0$ as the chi-squared distribution with two degrees of freedom, and determine the standard deviation by fitting the cumulative distribution function. In each run, we can derive the 95% confidence levels for $g_{\text{NN}}$ limits over the amplifier bandwidth with a width of 0.0358 Hz (corresponding to 0.15 feV), as shown in Fig. 4a. The detailed data-processing and exclusion procedure is discussed in the Supplementary Information. By scanning the bias field with a step of 0.0358 Hz, limits on the axion–nucleon coupling constants $g_{\text{NN}}$ over the entire mass range are obtained, as shown in Fig. 4b (blue line). The present work explores a mass range from 15 to 78 feV overlapping with the CASPeR–ZULF experiment, and improves the previous limits by more than five orders of magnitude. A recent work derives ALP limits below 200 feV based on the decade-old comagnetometer data from previously published work. That work cannot access ALPs at higher Compton frequencies due to the sensitivity loss of comagnetometers. In contrast, we extend the ALP search to so-far unconstrained regions of the parameter space from 200 to 744 feV. We check the viability of our data analysis procedure by inserting simulated ALP signals into our data and verify that the analysis method can recover the resonant and non-resonant ALP signals with their correct coupling strengths (Supplementary Section V). We note that preliminary theoretical investigations in a recent work have shown that if the amplitude fluctuations for ultralight ALPs are taken into account, then the inferred limits may be weakened by factors of order of unity at the 95% confidence level. However, these investigations are still at a preliminary stage and are beyond the scope of this article.

We note that the experimental sensitivity to $g_{\text{NN}}$ scales as $t^{-1/2}$ as a function of measurement time $t$. As an initial search, we report experimental results for 100 probed ALP-mass windows (Fig. 4b, red line) centred at different bias fields and with a width of 0.15 feV, where each window is obtained using 5 h of data. Compared with 100 s search sensitivity, we achieve one order of magnitude improvement on the ALP search sensitivity, for example, reaching $2.9 \times 10^{-9} \text{GeV}^{-1}$ at 67.5 feV (95% confidence level). We note that our laboratory limits are comparable to the stringent astrophysical limits obtained from supernova SN 1987A cooling. Recently, some works have placed tighter astrophysical limits from SN 1987A and neutron stars; nonetheless, the astrophysical limits depend on the model and can be evaded under certain scenarios, as described in refs. 44,45. To complete the 5 h ALP searches in the entire range from 1 to 200 Hz, we propose to set up multiple spin-based amplifiers and cooperate with other research groups that have similar setups already in existence, enabling the simultaneous search for ALPs and thus reduce the total acquisition time down to one month. Moreover, the global network of optical magnetometers to search for exotic physics already has a number of very similar devices could potentially be configured to run the present resonant searches.

Although demonstrated for axion-like dark matter searches, our sensing technique can be immediately applied to search for a broad range of exotic fields and forces predicted by theories beyond the standard model. Recent theoretical developments have predicted the existence of other bosons that could be constituents of dark matter, for example, dark photons. Here we show that our measurement constrains the nuclear spin interactions with dark photons through the coupling of the dark photon electric field to the dark electric dipole moment (dEDM) and the coupling of the dark photon magnetic field to the dark magnetic dipole moment (dMMD) (Supplementary Fig. 12). We also constrain the nuclear-spin quadratic coupling with axions ($g_{\text{quad}}$ (refs. 26,28) (Fig. 4c)). Our achieved limits surpass the previous laboratory limits by several orders of magnitude and are beyond the astrophysical limits over a large part of the explored mass range. The above limits for dark photon–nucleon interactions are from the 100 s dataset and could be further improved based on our initial 5 h dataset with one order of magnitude. Details of $g_{\text{quad}}$ and $g_{\text{MMD}}$ are presented in Supplementary Section VI. In addition, numerous theories predict that ALPs can mediate new forces between objects. The approach is proposed based on the resonant effect between nuclear spins and the effective field induced by axion-mediated force and could substantially improve on current experimental limits set by astrophysics, but it has not yet been experimentally demonstrated. Our work has already demonstrated a feasible route towards resonant amplification of the signal from exotic ALP fields and is also suited for searching axion-mediated forces.
amplification factor of $m$ centred at $v_0 = 12.80$ Hz. In addition, it is necessary to optimize the amplification performance of the spin-based amplifier at $v_0 = 12.80$ Hz. The grey line shows the limit given by the CASPer–ZULF experiment. The blue-shaded region is excluded from our measurements (100 s for each run) at the 95% confidence level. The red lines show our advanced sensitivity (5 h for each run) at 100 probed masses with a window width of 0.15 feV. The old comagnetometer limit is obtained from ref. 32, which analyses the old comagnetometer data from previously published work. The horizontal black line shows the laboratory searches for new spin-dependent forces and the astrophysical limit from supernova SN 1987A cooling. Limits on dark photon–nucleon coupling $g_{aNN}$ of nucleons with axion-like dark matter within a mass range from 8.3 to 744.0 feV. The blue-shaded region is excluded from our measurements (100 s for each run) at the 95% confidence level. The red lines show our advanced sensitivity (5 h for each run) at 100 probed masses with a window width of 0.15 feV. The grey line shows the limit given by the CASPer–ZULF experiment. The black line shows the astrophysical limit from supernova SN 1987A cooling. The horizontal black line shows the astrophysical limit from supernova SN 1987A cooling.

Fig. 4 | Results of axion-like dark matter search. a, Limits on coupling strength $g_{aNN}$ of nucleons with the axion-like dark matter within a mass range centred at $m_a = 52.94$ feV and with a width of 0.15 feV. The blue-shaded region (95% confidence level) is excluded from our 5 h measurement of the spin-based amplifier at $v_0 = 12.80$ Hz. b, Limits on coupling strength $g_{aNN}$ of nucleons with axion-like dark matter in the mass range from 8.3 to 744.0 feV. The blue-shaded region is excluded from our measurements (100 s for each run) at the 95% confidence level. The red lines show our advanced sensitivity (5 h for each run) at 100 probed axion masses with a window width of 0.15 feV, as shown in a. The grey line shows the limit given by the CASPer–ZULF experiment. The ‘old comagnetometer’ limit is obtained from ref. 32, which analyses the old comagnetometer data from previously published work. The horizontal black line shows the laboratory searches for new spin-dependent forces and the astrophysical limit from supernova SN 1987A cooling. Limits on dark photon–nucleon coupling $g_{aNN}$ of nucleons with axion-like dark matter within a mass range from 8.3 to 744.0 feV. The blue-shaded region is excluded from our measurements (100 s for each run) at the 95% confidence level. The red lines show our advanced sensitivity (5 h for each run) at 100 probed masses with a window width of 0.15 feV. The grey line shows the limit given by the CASPer–ZULF experiment. The black line shows the astrophysical limit from supernova SN 1987A cooling.

With the use of an optimized spin-based amplifier and a mass rotor, as recently demonstrated in refs. 50,51, it allows extending the search for new forces with better sensitivity than previous works.

A further improvement in experimental sensitivity to axion-like dark matter is anticipated. Increasing the volume of the vapour cell up to 100 cm$^3$ could enhance the $^{87}$Rb magnetometer sensitivity by a factor of about 10; it is further possible to achieve better magnetometer performance using multi-pass vapour cells. In addition, it is necessary to optimize the amplification performance of spin-based amplifiers for ALP signals. The most efficient way would be using $^3$He–K systems, because $^3$He spins have longer coherence time ($T_2 \approx 20$ s here), allowing one to achieve an amplification factor of $\eta \approx 10^4$. In addition, the $^3$He–K system has five orders of magnitude smaller spin-destruction cross section than $^{133}$Xe–Rb systems, and thus, the K magnetometer can still achieve femtotesla sensitivity, as demonstrated in ref. 52. Hence, the magnetic sensitivity based on $^3$He spin amplifier could probably reach 1 aT Hz$^{-1}$ level within the amplifier bandwidth, yielding experimental sensitivities of $|g_{aNN}| \approx 10^{-13}$ GeV$^{-1}$, $|g_{aNN}| \approx 10^{-12}$ GeV$^{-1}$, $|g_{aNN}| \approx 10^{-11}$ GeV$^{-1}$ and $|g_{aNN}| \approx 10^{-4}$ GeV$^{-1}$. Our approach can be extended to a network of synchronized sensors: the apparatus used in our experiment is at a small scale and inexpensive. Such a sensor network is promising to compose an exotic-field telescope array for multi-messenger astronomy, as recently proposed, and enables an improvement in sensitivity with the inverse square root of sensor number and allows to distinguish an exotic-physics signal from spurious noise. Moreover, correlating the readouts of many sensors in such a network could help address the stochastic fluctuations of bosonic dark matter.

Online content
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Articles

Nature Physics

26. Wu, T. et al. Search for axionlike dark matter with a liquid-state nuclear spin experiment (CASPEr). In *Nature* 562, 63–66 (2018).

25. Abel, C. et al. Search for axionlike dark matter through nuclear spin parity nonconservation, anapole moments, electric dipole moments, P-odd interactions of cosmic fields with electrons, and spin-gravity and spin-axion momentum couplings. *Phys. Rev. D* 89, 043522 (2014).

24. Kimball, D. F. J. et al. Overview of the cosmic axion spin precession experiment (CASPEr). In *Microwave Cavities and Detectors for Axion Research* 105–121 (Springer, 2020).

23. Kimball, D. F. J. et al. Overview of the cosmic axion spin precession experiment (CASPEr). In *Microwave Cavities and Detectors for Axion Research* 105–121 (Springer, 2020).

22. Stadnik, Y. & Flambaum, V. Axion-induced effects in atoms, molecules, and nuclei: parity nonconservation, anapole moments, electric dipole moments, and spin-gravity and spin-axion momentum couplings. *Phys. Rev. D* 89, 043522 (2014).

21. Graham, P. W. & Rajendran, S. Axion dark matter detection with cold nuclei. *Phys. Lett. B* 122, 121802 (2019).

20. Roberts, B. et al. Limiting P-odd interactions of cosmic fields with electrons, protons, and neutrons. *Phys. Rev. Lett. 113*, 081601 (2014).

19. Budker, D., Graham, P. W., Ledbetter, M., Rajendran, S. & Sushkov, A. O. Search for axion-like dark matter with ferromagnets. *Nat. Phys.* 17, 79–84 (2020).

18. Gramolin, A. V., Aybas, D., Johnson, D., Adam, J. & Sushkov, A. O. Search for axion-like dark matter with ferromagnets. *Nat. Phys.* 17, 79–84 (2020).

17. Ouellet, J. L. et al. First results from ABRACADABRA-10 cm: a search for sub-μeV axion dark matter. *Phys. Rev. Lett.* 122, 121802 (2019).

16. Beznogov, M. V., Rrapaj, E., Page, D. & Reddy, S. Constraints on axion-like particles and nucleon pairing in dense matter from the hot neutron star in HESS J1731–347. *Phys. Rev. C* 98, 035802 (2018).

15. Braine, T. et al. Extended search for the invisible axion with the axion dark matter experiment. *Phys. Rev. Lett.* 124, 101303 (2020).

14. Bradley, R. et al. Microwave cavity searches for dark-matter axions. *Rev. Mod. Phys.* 75, 777–817 (2003).

13. Anastassopoulos, V. et al. New CAST limit on the axion–photon interaction. *Nat. Phys.* 13, 584–590 (2017).

12. Svec, P. & Witten, E. Axions in string theory. In *J. High Energy Phys.* 2006, 051 (2006).

11. Ikastorza, I. G. & Redondo, J. New experimental approaches in the search for axion-like particles. *Prog. Part. Nucl. Phys.* 102, 89–159 (2018).

10. Kamionkowski, M., Kuroda, S. & Melchiorri, M. Axion-induced effects in astrophysics. *Phys. Rev. C* 82, 045808 (2010).

9. Preskill, J., Wise, M. B. & Wilczek, F. Cosmology of the invisible axion. *Phys. Rev. Lett.* 51, 1440–1443 (1983).

8. Peccei, R. D. & Quinn, H. R. CP conservation in the presence of weak interactions by using SmCo5 spin sources. Preprint at https://arxiv.org/abs/2011.12617

7. Aprile, E. et al. First dark matter search results from the XENON1T experiment. *Phys. Rev. Lett.* 119, 181301 (2017).

6. Bertone, G. & Tait, T. M. A new era in the search for dark matter. *Nature* 522, 51–56 (2015).

5. Akimov, A. V., Aybas, D., Johnson, D., Adam, J. & Sushkov, A. O. Search for axion-like dark matter with ferromagnets. *Nat. Phys.* 17, 79–84 (2020).

4. Bertone, G. & Hooper, D. History of dark matter. *Phys. Rev. D* 97, 055006 (2018).

3. Safronova, M. et al. Search for new physics with atoms and molecules. *Rev. Mod. Phys.* 90, 025008 (2018).

2. DeMille, D., Doyle, J. M. & Sushkov, A. O. Probing the frontiers of particle physics with tabletop-scale experiments. *Science* 357, 990–994 (2017).

1. Bertone, G. & Hooper, D. History of dark matter. *Rev. Mod. Phys.* 90, 045002 (2018).
Data availability
Source data are provided with this paper. All other data that support the plots in this paper and other findings of this study are available from the corresponding author upon reasonable request.

Code availability
The code that supports the plots in this paper is available from the corresponding author upon reasonable request.

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Author contributions
M.J. designed the experimental protocols, analysed the data and wrote the manuscript. H.S. performed the experiments, analysed the data and wrote the manuscript. A.G. analysed the data and edited the manuscript. X.P. proposed the experimental concept, devised the experimental protocols and edited the manuscript. D.B. contributed to the design of the experiment, and proofread and edited the manuscript. All the authors contributed with discussions and checking the manuscript.

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The authors declare no competing interests.

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