New Constraints on Short-Range Forces Coupling Mass to Intrinsic Spin

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A new device that we refer to as the spherical superconducting torsion balance has been used to search for a new force coupling mass to intrinsic spin. Our experimental approach also employs a novel spin-source geometry that allows unprecedented sensitivity in the range 100 μm $< \lambda < 5$ mm. We place new limits on the dimensionless coupling constant of such an interaction of $g_p^e g_s < (-1.9 \pm (1.3)_{\mathrm{stat}} \pm (1.5)_{\mathrm{syst}}) \times 10^{-26}$ for $\lambda > 10$ mm at 1σ confidence. At a range of 1 mm our most relaxed limit is $g_p^e g_s < 1.5 \times 10^{-24}$.

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Introduction.—The existence of new macroscopic interactions coupling to intrinsic spin has been suggested by a number of authors [1–4]. Moody and Wilczek [5] proposed an interaction potential, generated by a boson with spin-zero

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

where g_s refers to the coupling strength at the scalar vertex (here taken to be a nucleon) and g_p^e is the coupling strength at the pseudoscalar vertex, which in the current experiment is the electron. If the mass of the exchange particle is m, the range of the interaction is given as $\lambda = \hbar/mc$. The above potential violates parity, P, and time-reversal, T. At the present time the axion is arguably the most likely candidate particle for generating such a new interaction and may be detected in the near future as dark matter [6] or from solar emission [7]. Using the parametrization given above we can write $(g_p^e g_s)_{\mathrm{Axion}} < \theta/\lambda^2 \, 6 \times 10^{-33}$, where θ is constrained by experimental limits on the dipole moment of the neutron [8] to be less than about 10^{-9}. The mass of the axion is constrained by cosmology to be larger than 1 μeV, and by the neutrino signal from Supernova 1987a, to be less than 10 meV (20 μm $< \lambda_{\mathrm{Axion}} <$ 20 cm [9]. Interestingly, Zavattini *et al.* [10] have recently reported a positive result from an experiment that looks for a rotation in the plane of polarization of linearly polarized light as it passes through a transverse magnetic field and have argued that this could be due to a new boson whose mass would lie in the range of 1–1.5 meV (0.13 mm $<$ $\lambda < 0.2$ mm).

A number of other experiments have placed constraints on the strength, $g_p^e g_s$, as a function of range. Recently Heckel *et al.* [11] used a torsion balance, with an attached spin-polarized test mass, to set the strongest constraints achieved so far at ranges larger than 1 m. In the range 10 cm $< \lambda <$ 1 m the best constraints come from Youdin *et al.* [12] who compared the relative precession frequencies of Hg and Cs magnetometers as a function of the position of masses with respect to an applied magnetic field. There are several other experiments, including this work, which have aimed at placing limits at considerably shorter ranges. Ni and colleagues [13] used a SQUID in an attempt to detect the change in polarization induced in a paramagnetic salt induced by the motion of an unpolarized source mass. This experiment sets the strongest constraints in the range 5 mm $< \lambda <$ 10 cm. We must note that detection of a force due to axion exchange lies outside the capability of the work reported in this Letter and all previous experimental searches.

Experimental.—We have developed a new instrument, which we refer to as a spherical superconducting torsion balance [14], shown schematically in Fig. 1(a). This instrument comprises a float that is levitated by the magnetic pressure generated by current flow in a superconducting coil. The substrate of the coil forms part of a sphere and the float is in the form of a spherical shell whose geometrical center coincides with that of the coil substrate when levitated. The float is manufactured from electrodeposited copper and its inner surface is coated with a lead film of thickness approximately 10 μm. Three test masses manufactured from oxygen-free high-conductivity copper are suspended from the rim of the float on 1 mm diameter copper tubes. The test masses are 30 mm long with a

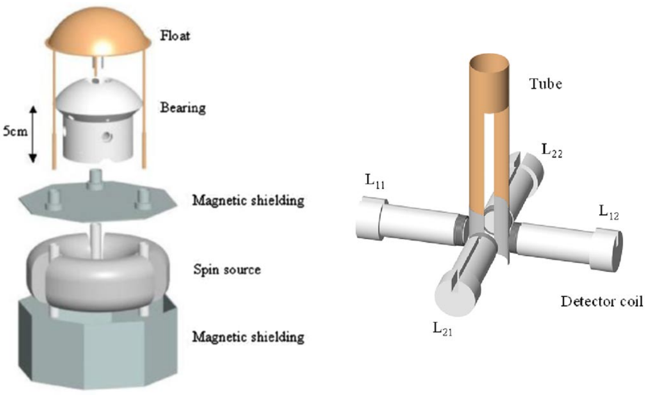

FIG. 1 (color online). (a) Exploded view of the spherical superconducting torsion balance. The magnetic shielding around the balance is not shown. (b) Detailed view of the rotation detector.

diameter of 3 mm. The total mass of the float is 18 g and each test mass has a value of 1.9 g. Attached to the underside of the float at its pole is a copper tube [shown in detail in Fig. 1(b)] that extends below the float equator. Two quadrants are cut from the lower section of the tube and the remaining segments are coated on both sides with lead of thickness approximately 10 mm. Four sensor coils are arranged radially in the equatorial plane of the bearing substrate adjacent to the edges of the segments of the tube. The centers of the test masses are 43 mm from the axis of rotation and the moment of inertia of the float is approximately 2×10^{-5} kg m^2. The float is free to oscillate as a near-perfect gimbal and its rotation about the lab vertical is detected using an inductive readout coupled to a quantum design dc SQUID magnetometer. Figure 2 shows a schematic of the inductive readout circuit. Persistent currents can be stored in each of the detector loops, which contain coil pairs L_{11}/L_{12} and L_{21}/L_{22}, using heat switches $\mathrm{HS}_1/\mathrm{HS}_2$ and the input charging transformer FT_1. Rotation of the float increases the inductance of one coil pair and reduces the inductance of the other. Modulation of the sensor-coil inductances creates a change in current in each detector loop due to flux conservation and this is coupled to the SQUID via the differential output transformer FT_2. The coil pairs are wound in such a way that they measure the sum of the flux coupling to each coil. This design was favored over a gradiometer configuration due to our need to measure leakage fields (see below). With a persistent current of 1 A stored in each detector branch the magnetic circuit generates a restoring torque which is equivalent to an oscillation period of 40 s. All superconducting magnetic circuits are fabricated from lead except for the loop connected to the SQUID which is niobium. The torsion balance and spin-source assembly are contained in a vacuum vessel immersed in liquid helium at atmospheric pressure in a Dewar. Helium gas inside the vacuum vessel gives a pressure, measured at room temperature, of approximately 0.1 Pa.

We have conceived a novel spin-source geometry that was manufactured by G. Rochester, D. Shaul, and T. Sumner of Imperial College London, UK. The design and performance of the spin-source will be discussed in detail elsewhere [15,16]. A toroidal electromagnet (shown in Fig. 1), constructed from soft pig-iron with permeability $\mu \approx 100$ at 4.2 K, is cut into three segments and wrapped with niobium wire. A tube of soft ferromagnetic material ($\mu > 100$ at 4.2 K, inner radius 4.5 mm and outer radius 6 mm) is located within each pole gap in the electromagnet and a test mass hangs coaxially within each tube. When a current (peak-peak amplitude of 1.8 A) is driven through the windings, a field of approximately 20 mT (as measured by a Hall-probe), is generated at the exterior of each tube. This field polarizes the electrons in the tube, which in turn generate a field that, in the limit of infinite permeability, would exactly cancel the external field inside the tube. The ferromagnetic tubes are lined with niobium (inner radius 3.5 mm) to further eliminate field leakage to the test masses. The outer cylindrical surface of the tubes [15] therefore provides a local source for the interaction described by Eq. (1). As the shielding currents in the superconductor are produced by Cooper pairs with zero net spin, these electrons are not a source for the potential described in Eq. (1). Further, the electron polarization at the surfaces of the pole pieces of the electromagnet are sufficiently far from the test masses that they do not contribute a significant spin signal. We estimate that there are approximately 10^{22} aligned electron spins per tube. The toroidal electromagnet is kinematically supported independently of the lined ferromagnetic tubes and the entire assembly is encased in a lead enclosure to magnetically isolate it from the torsion balance when operating at 4.2 K. The torsion balance is also enclosed in a separate lead shield [not shown in Fig. 1(a)].

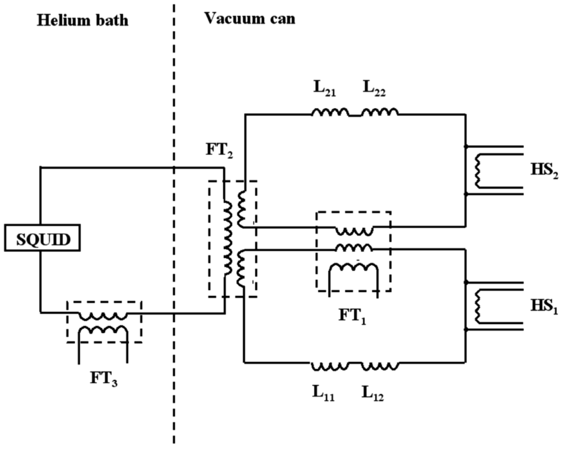

FIG. 2. The rotation detector circuit.

Results.—The experimental procedure consisted of measuring the oscillation of the torsion balance that was coherent with the sinusoidal current flowing through the windings of the spin-source at a frequency, ω, of 8 mHz. Data taking runs lasted typically 3 h and achieved a sensitivity to coherent torques of about 3×10^{-15} N m. Our initial experiments revealed coherent signals that were not constant in magnitude and phase and were judged to be due to systematic effects that we then proceeded to eliminate. We categorized these effects as either thermal or magnetic.

We estimated the net heat loss per cycle due to the hysteretic loss of stored magnetic energy in the spin-source assembly, using Rayleigh's law [17], to be approximately 13 μW. If we assume that the instantaneous power generated in a ferromagnet is given by $\dot{Q} = H\frac{dB}{dt}$ then it follows that, provided the B-field waveform has a constant offset and only odd harmonics, there is no heating effect at ω. However, a constant offset in the H field can potentially produce a signal at frequency ω. It is known that at room temperature Rayleigh's law gives an incomplete picture of heating due to magnetization, and the magnetocaloric effect [18], for example, can lead to changes in the temperature of ferromagnets. We directly measured the change in temperature of the toroid at 4.2 K for a variety of spin-source current amplitudes and offsets and observed that an offset in the spin-source current could produce temperature changes and torques that were coherent with the spin-source modulation and also at frequencies of 2ω. It is likely that a temperature change in the toroid generates spurious torques through the change in the configuration of trapped flux coupling the float to the bearing (see below). We avoided significant thermal ω-torques ($<10^{-15}$ N m) by ensuring that the offset current in the spin-source was less than 2 mA for all experimental runs.

A concept that is useful for eliminating systematic magnetic torques is "pseudo-time reversal". We can mimic time reversal by reversing the spin and angular momentum of all electrons participating in the experiment. We refer to this as pseudo-time reversal. If the measured torque changed sign after this process this would be evidence for any interaction violating T. We thus performed alternate data runs with the polarities of the currents in the spin source, levitation, and detector coils reversed. We were unable to achieve perfect pseudo-time reversal as we could not easily change the sense of the bias current in the SQUID. T violation would thus result in an apparent torque with a *nonzero mean* when the results were averaged across the data runs of both polarities. Note that it is not possible to eliminate heating effects using this technique as they depend on the square of the current flowing in the spin-source windings.

Any permanent dipole moment, $m(\phi)$, on the float would not be reversed by the pseudo T reversal described above. The magnetic potential energy of the float can be written

$$\begin{aligned} U_{\text{mag}} &= -\left\{\vec{m}(\phi) - \frac{\chi}{\mu_0} V(\vec{B}_0 + \vec{B})\right\} \cdot (\vec{B}_0 + \vec{B}_{\text{mod}}) \\ &= -\vec{m}(\phi) \cdot (\vec{B}_0 + \vec{B}_{\text{mod}}) + \frac{\chi}{\mu_0} V \vec{B}_0 \cdot \vec{B}_0 \\ &\quad + \frac{2\chi}{\mu_0} V \vec{B}_0 \cdot \vec{B}_{\text{mod}} + \frac{\chi}{\mu_0} V \vec{B}_{\text{mod}} \cdot \vec{B}_{\text{mod}}), \end{aligned} \tag{2}$$

where V is the volume of float and χ is its susceptibility [$\chi_{\text{Cu}} \approx -9 \times 10^{-6}$(SI)]. The quantity, B_{mod} is the component of the magnetic field at the location of the float that is modulated and B_0 is the value of a permanent offset in the field due perhaps to a remnance in the toroid. Only the first and third terms in Eq. (2) can generate a torque at ω. We were able [15,19] to show that the magnetic torques acting directly on the test masses were negligible in separate experiments. We measured the susceptibility and permanent dipole moment of one test mass by measuring the torque on the float due to a known field and field gradient. We also used a SQUID search coil to establish upper limits for B_{mod} in the region of the test masses.

Despite the double layer of magnetic shielding between the spin-source assembly and the torsion balance, we detected an output at frequency ω from the SQUID while the float was not levitated. This field had a magnitude of approximately 10^{-11} T and varied at the 10% level between data runs. We believe that this was due to motion of trapped flux in the lead shields. There was therefore the possibility of ω-torques being generated by the product of this leakage field and a dipole moment associated with flux trapped in the lead films on the float. To minimize this source of systematic uncertainty we heated the contents of the vacuum enclosure above the transition temperatures of lead and niobium between each change in polarity. This ensured that any induced magnetic moment would reverse sign between each data set taken with each polarity. Figure 3 shows the data taken from two campaigns. It is evident, particularly in the data from the second campaign, that there is a bias for the polarity labeled + to be negative and vice versa and the scatter in the data is not consistent with the uncertainties with each datum. Reversal of the polarity of the induced moments on the float did not, however, guarantee that the systematic torques averaged out over the course of the entire experiment as variations in the levitation process potentially introduces a variable geometrical factor in the torque. Such variations could be responsible for the difference in the character of the data from each campaign.

We estimated the magnitude of the magnetic moment on the float (excluding the test masses), m_f, by coupling a flux to the output coil of the detector circuit using flux transformer FT_3 (shown in Fig. 2). This flux produces a direct output in the SQUID but also couples a flux into the sensor-coil loops. In the absence of a finite m_f this flux produces a torque on the float due to the geometry of the rotation sensor. The component of m_f which is perpendicular to the net flux in the detector coils, say m_x, will generate an additional torque. The net effect is that the difference between the SQUID output induced by the input flux when the float is levitated and at rest can be used to determine a value for m_x. During the second campaign we measured values of m_x after each change in polarity giving a standard deviation (scatter) of the moments of, σ_{mx}, 3.0×10^{-4} Am^2 and a mean value of -1.6×10^{-4} Am^2. These values are consistent with flux being trapped in the lead films on the float

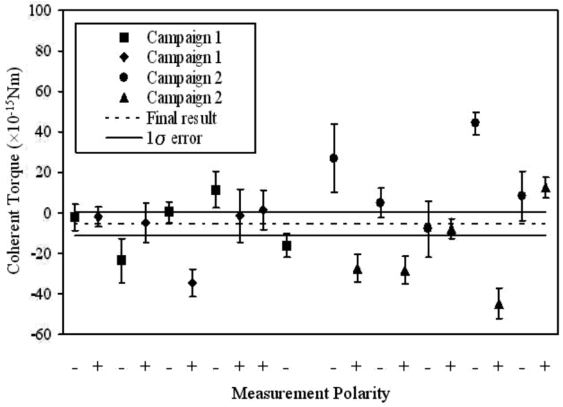

FIG. 3. Summary of the data taken during two campaigns as a function of the measurement polarity.

TABLE I. Summary of the mean torques and uncertainties obtained from the two data campaigns.

	Campaign 1		Campaign 2	
$\times 10^{-15}$ N m	Polarity +	Polarity −	Polarity +	Polarity −
Torque	−8.3	−6.0	−19.1	15.3
Uncertainty	6.7	6.2	9.8	9.1
Combined Torque	−7.1 ± 4.6		−1.9 ± 6.7	

when persistent currents are stored in the detector and/or levitation coils. The measured torques were fitted to the values of m_x giving a gradient of $(2.2 \pm 3.0) \times 10^{-11}$ T, which is consistent with the pick up from the spin source measured by the SQUID with the float at rest. As it was only possible to measure one component of the moment it was not possible to directly correct the data for this systematic effect and the fit cannot be expected to be statistically "good". We estimated the magnitude of the systematic magnetic torque by making the following assumptions: the standard deviation of one component of leakage magnetic field, σ_{Bx}, is 3.0×10^{-11} T and the standard deviations in the x and y components of the field and moment were identical. Propagation of these uncertainties across the data from both campaigns gives a systematic uncertainty in the mean torque of $\sigma_{\text{stat}} \approx 2/\sqrt{N}\sigma_{Bx}\sigma_{mx}$. With a total of 18 measurements we find $\sigma_{\text{stat}} = 4.2 \times 10^{-15}$ N m.

The mean torques and uncertainties for each polarity and each data campaign are shown in Table I. The weighted mean of the combined torques from both campaigns gives a final result $\Gamma_{\text{sc}} = (-5.4 \pm (3.8)_{\text{stat}} \pm (4.2)_{\text{syst}}) \times 10^{-15}$ N m for the spin-coupling torque.

Conclusions.—Using the geometry of the spin-source assembly we can establish limits on the dimensionless coupling constant $g_p^e g_s(\lambda)$ as shown in Fig. 4. We have added the systematic and statistical uncertainties on Γ_{sc} in quadrature and combined them with the result to give the most relaxed constraints. This assumes that $g_p^e g_s$ is negative (perhaps indicating a vector-mediated interaction) and gives a final result of $g_p^e g_s < 1.5 \times 10^{-24}$ at a range of 1 mm (1σ confidence). Our result for ranges $\lambda > 10$ mm can be written $g_p^e g_s < (-1.9 \pm (1.3)_{\text{stat}} \pm (1.5)_{\text{syst}}) \times 10^{-26}$. We also show constraints from Ni and colleagues [13] and Youdin *et al.* [12]. It is also worth noting that Yen *et al.* [20] also give useful limits at ranges of order $\lambda = 1$ mm. However, a full discussion of systematic effects has not, so far, been published for this work.

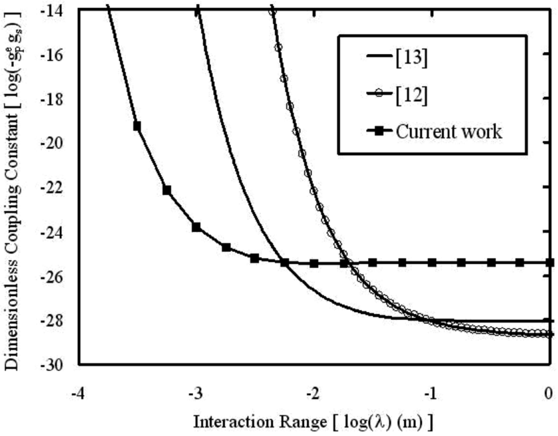

FIG. 4. Current limits on the strength of the dimensionless coupling constant $g_p^e g_s$ as a function of the interaction range.

The new instrument and novel spin-source assembly has allowed us to search for new forces with ranges $\lambda > 100$ μm with unprecedented precision. We intend to improve the magnetic and thermal isolation of the spin-source assembly and are proceeding with the manufacture and testing of a second generation SSTB that is based on niobium.

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