Test of the Universality of Free Fall with Atoms in Different Spin Orientations

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We report a test of the universality of free fall by comparing the gravity acceleration of the ^{87}Rb atoms in $m_F = +1$ versus those in $m_F = -1$, of which the corresponding spin orientations are opposite. A Mach-Zehnder-type atom interferometer is exploited to alternately measure the free fall acceleration of the atoms in these two magnetic sublevels, and the resultant Eötvös ratio is $\eta_S = (0.2 \pm 1.2) \times 10^{-7}$. This also gives an upper limit of 5.4×10^{-6} m^{-2} for a possible gradient field of the spacetime torsion. The interferometer using atoms in $m_F = \pm 1$ is highly sensitive to the magnetic field inhomogeneity. A double differential measurement method is developed to alleviate the inhomogeneity influence, of which the effectiveness is validated by a magnetic field modulating experiment.

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The universality of free fall (UFF) is one of the fundamental hypotheses in the foundation of Einstein's general relativity [1]. Traditional verifications of the UFF are performed with macroscopic bodies that weight differently or comprise different material [2–9] and have achieved a level of 10^{-13} [8,9]. There is also a lot of work investigating the possible violation of the UFF that is induced by spin-related interactions [10–17]. Two possible spin-related mechanisms for UFF breaking are spin-gravity coupling and spin-torsion coupling, of which the corresponding Hamiltonians read [18–20]:

$$H_{\text{spin-gravity}} = f(r)\vec{S}\cdot\hat{r},$$
$$H_{\text{spin-torsion}} = -c\vec{S}_T(r)\cdot\vec{S}/2, \qquad (1)$$

where $\vec{S}$ is the test mass spin, and $\vec{S}_T$ stands for the spacetime torsion. In Eq. (1), $\hat{r}$ points from the source to the test mass, $f(r)$ is an arbitrary scalar function of r, and c is the light speed. UFF tests related to spin-gravity coupling have been performed with polarized or rotating macroscopic bodies [19,21–27] and have achieved a precision of 10^{-9}. However, the precision decreases dramatically to a level of 10^{-5} when the result is reinterpreted in terms of a polarized nucleus and even to 10^{-3} in terms of a polarized electron [15,19]. This suggests a direct UFF test using quantum particles to investigate the spin-gravity coupling. Meanwhile, spin-torsion coupling is believed to only affect matter with intrinsic spins [20,28,29], which makes spinful atoms a natural choice for torsion experiments. Experiments based on atomic comagnetometers have given an upper bound on the spacetime torsion of 2.4×10^{-15} m^{-1} [20,30]. According to the model in Refs. [31,32], the torsion may change along with space. This space dependence implies a possible torsion gradient, which has hitherto not been experimentally questioned.

UFF tests using quantum objects have earlier been performed with a neutron interferometer [33], and in recent years, were carried out with neutral atoms by comparing the free fall acceleration between different atoms or between atoms and macroscopic masses [34–40]. Up to this time, if the motivations of these tests are not distinguished, the best test precision using quantum objects is 7×10^{-9} [34]. Further tests on a quantum basis are still ongoing, which aim at reaching a higher precision [40–43] and also covering more possible breaking effects. The possible breaking of the UFF by spin-related couplings in the quantum realm has only been tested in few experiments. One representative experiment was done in 2004, in which the difference of the free fall acceleration with atoms in two different hyperfine states was tested at 1.2×10^{-7}, in addition to comparing the free fall acceleration between ^{85}Rb and ^{87}Rb [35]. More recently, Tarallo *et al.* [44] performed a UFF test using the bosonic ^{88}Sr isotope versus the fermionic ^{87}Sr isotope at 1.6×10^{-7} by Bloch oscillation. In their experiment, the ^{87}Sr atoms were in a mixture of different magnetic sublevels, resulting in an effective sublevel of $\langle m_F\rangle = 0$. They also gave an upper limit for the spin-gravity coupling by analyzing the resonance linewidth broadening caused by the possible different free fall accelerations between different magnetic sublevels. However, we note that the possible anomalous spin-spin couplings [24,45,46] or dipole-dipole interactions [47] between the ^{87}Sr atoms in different magnetic sublevels may disturb, or even overwhelm, the spin-gravity coupling effects in their experiment. Given that most models describing spin-related couplings imply a dependence on the orientation of the spin, we perform a new UFF test with

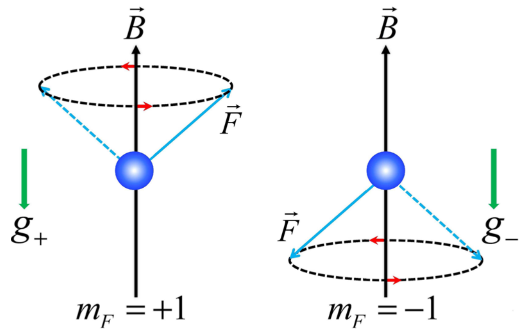

FIG. 1. Schematic of the spin orientations for ^{87}Rb atoms in magnetic sublevel $m_F = +1$ versus $m_F = -1$ of the $5^2S_{1/2}$ hyperfine levels. The bias magnetic field $\vec{B}$ defines the external direction to which the atomic spin is referenced. The total angular momentum $\vec{F}$ of each atom precesses around $\vec{B}$.

^{87}Rb atoms prepared in two opposite spin orientations (Fig. 1), namely, $m_F = +1$ versus $m_F = -1$. The free fall accelerations of ^{87}Rb in $m_F = +1$ and $m_F = -1$ are sequentially measured and compared, which determines the spin-orientation related Eötvös ratio as

$$\eta_S \equiv 2(g_- - g_+)/(g_- + g_+), \tag{2}$$

where the gravity acceleration of the atoms in $m_F = +1$ ($m_F = -1$) is denoted as g_+ (g_-). This provides a direct way to test the UFF which is the spin orientation related on a quantum basis. According to Eq. (1), if the origin of a possible violation of the UFF is attributed to spin-torsion coupling, the torsion gradient can be linked to η_S as

$$\partial_z(S_T)_z = \eta_S m(g_- + g_+)/c\Delta S_z, \tag{3}$$

where m is the atom mass, and ΔS_z stands for the difference of the spin projections onto the vertical direction. Thus, the possible torsion gradient can also be probed through this kind of UFF test.

The experiment is carried out in an atom gravimeter reported in detail in Ref. [48]. We perform alternate measurements of gravity acceleration with ^{87}Rb atoms in the two magnetic sublevels $m_F = +1$ and $m_F = -1$. The major advantage of an atom interferometer over the traditional UFF tests of spin-related effects is the high purity of the spin polarization in atomic ensembles obtained by stimulated Raman transition based state preparation [49]. A great challenge in our experiments is to alleviate the influence of the magnetic field, since interferometers with atoms in the sublevels $m_F = \pm 1$ are highly sensitive to magnetic field inhomogeneity. Three strategies have been applied to reduce this influence.

First, the interfering region is carefully selected and compensated to reduce the inhomogeneity of the bias magnetic field. The magnetic field throughout the shielded interfering tube is mapped [50,51], and a relatively homogeneous region at about 742 mm in height above the magnetic-optical trap center is chosen for the interfering process. The magnetic field there varies less than 0.1 mG over several millimeters in the vertical direction with a 115 mG bias magnetic field. Moreover, the inhomogeneity in this interfering region is further decreased to 0.01 mG by utilizing an anti-Helmholtz compensating coil with an injection current of 110 μA.

Second, the atom fountain apex is set in the selected interfering region, which offers two advantages in our UFF test. For one thing, the apex moment is among the interfering process, making a quasisymmetrical trajectory for atoms [Fig. 2(a)]; thus, the influence of the magnetic field inhomogeneity cancels significantly. This cancelation assures a relatively long interrogation time (a separation time as large as $T = 25$ ms is allowed here, quite larger than $T = 1$ ms in Refs. [50,51]), which effectively enlarges the signal of the gravity acceleration. For another, near the fountain apex, the center of the atomic cloud only moves vertically 4.2 mm during the interfering process. In such a short distance, a binomial model for the magnetic field inhomogeneity is appropriate, which validates the following systematic error correction.

Finally, a double differential measurement method is developed to further correct the magnetic field inhomogeneity effect. The phase shift induced by the magnetic field inhomogeneity can be calculated [50–52] by $\varphi_B = 2\alpha[\int_0^T B(z(t))dt - \int_T^{2T} B(z(t))dt]$, where α is the strength of the first-order Zeeman shift for ^{87}Rb atoms in the $5^2S_{1/2}$ state, $B(z(t))$ denotes the magnetic field at $z(t)$, and T is the separation time between Raman laser pulses. Considering a binomial variation model of $B(z(t)) = B(z_0) + \gamma_1[z(t) - z_0] + \gamma_2[z(t) - z_0]^2/2$ [here, γ_1 (γ_2) is the first (second) order inhomogeneity coefficient, and z_0 stands for an arbitrary reference point in the selected region], the phase shift induced by the gravity acceleration and the magnetic field gradient is expressed as

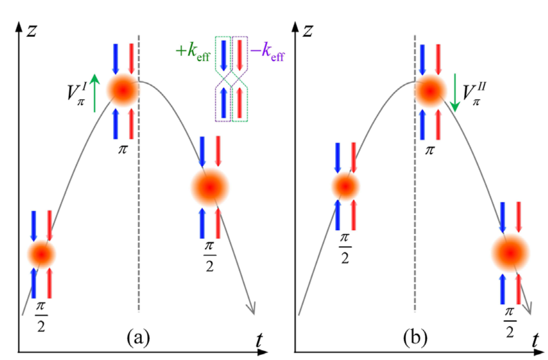

FIG. 2. Schematics of the double differential measurement method, where the spheres represent the atomic clouds at the corresponding locations in the time-space frame. In each configuration of V_π, the direction of $\boldsymbol{k}_{\rm eff}$ is modulated between $+k_{\rm eff}$ and $-k_{\rm eff}$. For (a) versus (b), the time for the interfering π pulse is changed, which modulates V_π between $V_\pi^{\rm I}$ and $V_\pi^{\rm II}$.

$$\Delta\varphi_{m_F}^{\pm} = \mp k_{\mathrm{eff}} g_{m_F} T_{\mathrm{eff}}^2 + 2\alpha m_F T^2 (V_\pi \mp V_r/2) \times [\gamma_1 + \gamma_2 (V_\pi + gT/4 \mp V_r/2)T + \gamma_2 (z_{\mathrm{s}} - z_0)], \tag{4}$$

where the superscript $+(-)$ indicates the corresponding case of the same (opposite) direction between the effective Raman laser wave vector $\boldsymbol{k}_{\mathrm{eff}}$ and the local gravity acceleration. $T_{\mathrm{eff}} \equiv T\sqrt{1 + 2\tau/T + 4\tau/\pi T + 8\tau^2/\pi T^2}$ is the effective separation time accounting for the effect of the finite $\pi/2$ Raman pulse duration τ [53,54]. In Eq. (4), the second term corresponds to the effect induced by the magnetic field inhomogeneity, where V_r is the recoil velocity, V_π is the averaged vertical velocity of the atoms in $F = 1$ at the moment of the interfering π pulse, and z_{s} is the site where the interfering process begins. For an ideal case, the interfering π pulse should be switched on at the apex time to make a completely symmetrical trajectory for the atoms during the interfering process. However, in practical atom gravimeters [55], there should be a time difference between the interfering π pulse and the moment of the atomic cloud reaching the apex to obtain a non-negligible Doppler shift for distinguishing the $\pm k_{\mathrm{eff}}$ configurations (here, it is around 3 ms).

In order to get rid of the second term in Eq. (4), as already adopted in typical atom gravimeters [56–58], the $\boldsymbol{k}_{\mathrm{eff}}$ direction is reversed to make a differential measurement for each m_F [Fig. 2(a)]. From this reversing $\boldsymbol{k}_{\mathrm{eff}}$ method, a differential mode measurement result $[\Delta\varphi_{m_F}^d \equiv (\Delta\varphi_{m_F}^+ - \Delta\varphi_{m_F}^-)/2]$ and a common mode measurement result $[\Delta\varphi_{m_F}^c \equiv (\Delta\varphi_{m_F}^+ + \Delta\varphi_{m_F}^-)/2]$ can be obtained. However, there is a residual influence of the magnetic field inhomogeneity in $\Delta\varphi_{m_F}^d$ due to the opposite directions of the recoil velocities between the $+k_{\mathrm{eff}}$ and $-k_{\mathrm{eff}}$ configurations. With only the first order magnetic field inhomogeneity considered, this residual effect can be corrected using γ_1 estimated from $\Delta\varphi_{m_F}^c$. To further reduce the inhomogeneity effect, the information of γ_2 is required to perform the correction. In this work, for each m_F, a secondfold measurement is performed by modulating V_π between two values (denoted as V_π^{I} and V_π^{II}). We find that the systematic error correction is simplest by setting $V_\pi^{\mathrm{I}} = -V_\pi^{\mathrm{II}} \equiv V_\pi^0$ [Fig. 2(a) versus Fig. 2(b)]. Through this double differential measurement, four combined measurement results are obtained. The explicit expressions for $\Delta\Phi_{m_F}^{dc} \equiv (\Delta\varphi_{m_F}^d[V_\pi^{\mathrm{I}}] + \Delta\varphi_{m_F}^d[V_\pi^{\mathrm{II}}])/2$ and $\Delta\Phi_{m_F}^{cd} \equiv (\Delta\varphi_{m_F}^c[V_\pi^{\mathrm{I}}] - \Delta\varphi_{m_F}^c[V_\pi^{\mathrm{II}}])/2$ are

$$\Delta\Phi_{m_F}^{dc} = -k_{\mathrm{eff}} g_{m_F} T_{\mathrm{eff}}^2 - \alpha m_F T^2 V_r [\gamma_1 + \gamma_2 (V_\pi^0 + gT/4)T],$$
$$\Delta\Phi_{m_F}^{cd} = 2\alpha m_F T^2 V_\pi^0 [\gamma_1 + \gamma_2 (V_\pi^0 + gT/4)T]. \tag{5}$$

We note that in deriving Eq. (5) from Eq. (4), z_s is a function of V_π. According to Eq. (5), the residual influence of the magnetic field inhomogeneity in $\Delta\Phi_{m_F}^{dc}$ can be corrected directly as $\Delta\Phi_{m_F}^{dc} + \Delta\Phi_{m_F}^{cd} \times (V_r/2V_\pi^0)$, which needs no knowledge of γ_1 and γ_2. Certainly, with the help of other combined results of the double differential measurement, γ_1 and γ_2 can be estimated.

In reversing the $\boldsymbol{k}_{\mathrm{eff}}$ differential measurement, it is important to prepare the atomic ensembles in the same average velocity between the $+k_{\mathrm{eff}}$ and $-k_{\mathrm{eff}}$ interfering configurations for each m_F, namely $V_{\mathrm{s}}^+ = V_{\mathrm{s}}^-$ (V_{s} denotes the average velocity of the atomic ensemble after the state preparation, and the superscript $\pm$ denotes the $\boldsymbol{k}_{\mathrm{eff}}$ configuration). Here, we explore an easy but reliable method to guarantee this equality. For the two interfering configurations, we implement the state preparations using the Raman lasers both configured in $+k_{\mathrm{eff}}$ with the same Raman laser effective frequency ω_{eff}. In this way, for each m_F, the state preparations are completely the same for the two interfering configurations. As for the modulation of V_π, the state preparation procedures are totally the same. A delay time of about $2V_\pi^0/g$ ($g \sim 9.79 \mathrm{m/s^2}$) is inserted in the timing sequence between the state preparation and the interfering process, which ensures $V_\pi^{\mathrm{II}} = -V_\pi^{\mathrm{I}}$.

In our experiment, V_π^{I} and V_π^{II} are measured for each m_F to calculate the correction. This velocity is obtained from the spectroscopy of the velocity-selective Raman transition [49] with a Raman π pulse applied at the right moment. The measured average velocities are $V_\pi^{\mathrm{I}} = 30.6(1)$ mm/s and $V_\pi^{\mathrm{II}} = -30.6(1)$ mm/s for the selected atoms in both $|F = 1, m_F = +1\rangle$ and $|F = 1, m_F = -1\rangle$. In the free fall acceleration measurement, for each m_F, one full interferometry fringe is obtained by scanning the chirp rate of ω_{eff} in 20 steps in each $\boldsymbol{k}_{\mathrm{eff}}$ configuration for each V_π. It takes 30 s for a full fringe with 1.5 s for one single shot measurement. Meanwhile, in order to reduce the effect of possible long-term drift, eight adjacent fringes are grouped as a cycle unit, with one fringe corresponding to one combination of $\boldsymbol{k}_{\mathrm{eff}}$, V_π, and m_F. The switches between the combinations are automatically controlled by the computer. It takes 10 h to repeat the cycle unit 150 times. The phase shifts are extracted by the cosine fitting from the fringes, from which the combination $\Delta\Phi_{m_F}^{dc}$ and $\Delta\Phi_{m_F}^{cd}$ can be calculated. The Allan deviation calculated from the consecutive measurement of $\Delta\Phi_{m_F}^{dc}$ shows a short-term sensitivity of about $3.5 \times 10^{-6} g/\sqrt{\mathrm{Hz}}$ for the gravity acceleration measurement with each m_F. The free fall acceleration for each m_F can be obtained from $\Delta\Phi_{m_F}^{dc} + \Delta\Phi_{m_F}^{cd} \times (V_r/2V_\pi^0)$, as shown in Fig. 3(a). The measured accelerations even show a faint trace of the tide. The difference of the accelerations between $m_F = +1$ and $m_F = -1$ is shown in Fig. 3(b), and the corresponding statistics result is $(-0.1 \pm 0.3) \times 10^{-7} g$.

In order to validate the efficiency of alleviating the influence of the magnetic field inhomogeneity in our UFF test by the double differential measurement, in addition to the 110 μA injection current for the compensating coils,

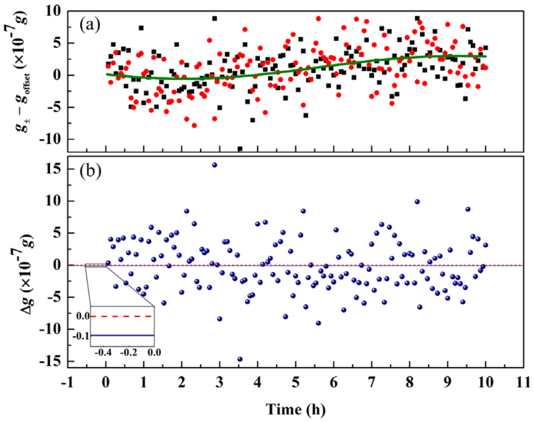

FIG. 3. Ten hours of data acquisition in our UFF test. (a) The measured free fall accelerations of $m_F = +1$ (red circle) and $m_F = -1$ (black square) with a common offset g_{offset}. The green line is the theoretical tide. (b) The difference between $m_F = +1$ and $m_F = -1$. The corresponding statistics average value (navy solid line) is also shown, accompanied with the null value (red dashed line).

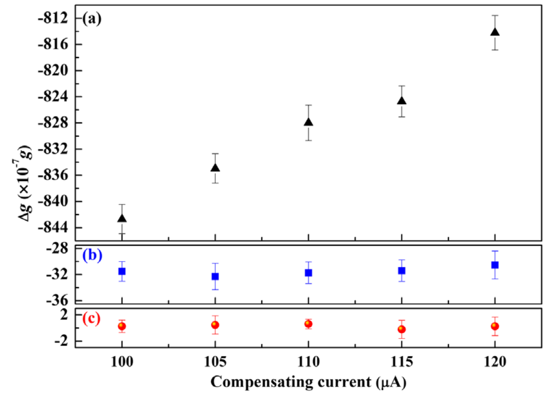

FIG. 4. Estimated Δg using different methods in the modulation of the injection current for the compensating coils. The data acquiring time for each injection current is only 1 h. In (a) no corrections are taken to decrease the magnetic field inhomogeneity influence, in (b) the conventional differential measurement is adopted to decrease the influence, and in (c) the influence is corrected using the double differential measurement. Note that the error bars here refer to the statistics standard deviation.

tests with the other four values of the current are also performed. The result is shown in Fig. 4, which is reported as $\Delta g \equiv g_- - g_+$ for each injection current. In Fig. 4(a), Δg is estimated by $\Delta g = (\Delta\varphi^+_{m_F=+1} - \Delta\varphi^+_{m_F=-1})/k_{\text{eff}}T^2_{\text{eff}}$, namely, the situation without any differential measurement to decrease the inhomogeneity influence. In Fig. 4(b), Δg is obtained by a differential measurement as

$$\Delta g = [(\Delta\varphi^d_{m_F=+1} + \Delta\varphi^c_{m_F=+1} \times V_r/2V^0_\pi) - (\Delta\varphi^d_{m_F=-1} + \Delta\varphi^c_{m_F=-1} \times V_r/2V^0_\pi)]/k_{\text{eff}}T^2_{\text{eff}}, \quad (6)$$

which is capable to correct the effect of the first order magnetic field inhomogeneity. In Fig. 4(c), Δg is obtained by the double differential measurement as

$$\Delta g = [(\Delta\Phi^{dc}_{m_F=+1} + \Delta\Phi^{cd}_{m_F=+1} \times V_r/2V^0_\pi) - (\Delta\Phi^{dc}_{m_F=-1} + \Delta\Phi^{cd}_{m_F=-1} \times V_r/2V^0_\pi)]/k_{\text{eff}}T^2_{\text{eff}}, \quad (7)$$

which further corrects the effect of the second order magnetic field inhomogeneity. According to Fig. 4(a), the influence of the magnetic field inhomogeneity changes dominantly with the injected current, and there is a huge offset at the $10^{-5}g$ level. In Fig. 4(b), the influence of the inhomogeneity has been suppressed by about 1 order of magnitude, but there is still a considerable residual effect, which is offset from zero at about $10^{-6}g$. In Fig. 4(c), there is no obvious dependence of Δg on the injection current. What is more important, the residual effect is also suppressed below the level of $10^{-7}g$, which proves that our correction based on this double differential measurement is quite effective.

In this UFF test, some disturbances, for example, which are induced by the ac-Stark shift, can be largely suppressed in the differential measurement for each m_F, and other disturbances, for example, which are induced by nearby masses or the tilt of the Raman lasers, are common for the atoms in $m_F = +1$ and $m_F = -1$, and are canceled in the final comparison. The main systematic error still comes from the effect associated with the magnetic field inhomogeneity. In this work the equality of V^+_{s} and V^-_{s} is well guaranteed by our special state preparation. However, the value of V^+_{s} and V^-_{s} drifts in a common way due to the variation of the Raman laser power as the room temperature changes periodically. Correspondingly, a peak-to-peak variation of 0.25 mm/s for V_π is observed, which on the one hand affects the cancellation in the double differential measurement and on the other hand limits the accuracy of the correction $\Delta\Phi^{dc}_{m_F} + \Delta\Phi^{cd}_{m_F} \times (V_r/2V^0_\pi)$. The corresponding contributed uncertainty on Δg is $1.2 \times 10^{-7}g$. We notice that there is a difference of $2\pi \times 2.8$ kHz/G for α between ^{87}Rb atoms in $F = 1$ versus $F = 2$, and the corresponding correction is about $0.3 \times 10^{-7}g$.

Combining all the contributions, the final resultant Eötvös ratio is $\eta_S = (0.2 \pm 1.2) \times 10^{-7}$. According to Eq. (3), this corresponds to a constraint of 5.4×10^{-6} m^{-2} for the gradient of the possible spacetime torsion (for this experiment, ΔS_z is $2|m_F|\hbar$) [59].

In conclusion, we have tested the UFF with atoms in different spin orientations based on a Mach-Zehnder-type atom interferometer, and a violation of the UFF is not observed at the level of 1.2×10^{-7}. This is the first direct spin-orientation related UFF test on a quantum basis, and also gives new upper bounds for the possible spin-gravity coupling and spacetime torsion gradient. Further improvement of the precision of this kind of UFF test can be realized by constructing a more homogeneous magnetic field or by exploiting internal state invariant atom interferometers [40,52,60–62]. In this work, in order to achieve this test precision, the local magnetic field inhomogeneity is decreased by compensation coils. The fountain apex is configured to make a quasisymmetrical trajectory for the atoms, which alleviates the inhomogeneity influence. Moreover, a double differential measurement method is developed to further correct the inhomogeneity effect. We found that this double differential measurement is also capable to alleviate the influence of the higher order inhomogeneity influence to a certain extent. These strategies may be illuminating for other high precision measurements using atom interferometry.

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