Null result for violation of the equivalence principle with free-fall rotating gyroscopes

J. Luo,[1,*] Y. X. Nie,[2] Y. Z. Zhang,[3,4,†] and Z. B. Zhou[1]

[1]*Department of Physics, Huazhong University of Science and Technology, Wuhan 430074, China*

[2]*Institute of Physics, Chinese Academy of Sciences, Beijing 100080, China*

[3]*CCAST (World Lab.), P.O. Box 8730, Beijing 100080*

[4]*Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100080, China*[‡]

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The differential acceleration between a rotating mechanical gyroscope and a nonrotating one is directly measured by using a double free-fall interferometer, and no apparent differential acceleration has been observed at the relative level of 2×10^{-6}. It means that the equivalence principle is still valid for rotating extended bodies, i.e., the spin-gravity interaction between the extended bodies has not been observed at this level. Also, to the limit of our experimental sensitivity, there is no observed asymmetrical effect or antigravity of the rotating gyroscopes as reported by Hayasaka *et al.*

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I. INTRODUCTION

It is well known that the spin interactions of elementary particles, spin-orbit coupling and spin-spin coupling, have been studied in both theory and experiment for a long time. Furthermore, gravitational couplings (i.e., the spin-gravitoelectric coupling [1,2] and the spin-gravitomagnetic coupling [3,4]) and spin-rotation coupling [5–7] between intrinsic spins and rotating bodies have been also investigated for a long time (see, e.g., Ref. [8]).

However, the status of research for rotation (spin-) coupling between macroscopic rotating bodies is vastly different. The spin-orbit coupling for the motion of a mechanical gyroscope was already well known in Newton's mechanics. With the exception of the spin-orbit coupling, on the other hand, Einstein's theory of general relativity also predicts the spin-gravitational coupling of a mechanical gyroscope, which has been investigated by many authors, e.g., see Ref. [8]. In particular, the Stanford Gravity Probe B (GPB) group has theoretically studied for a long time these types of gravitomagnetic effects and plans to perform a satellite orbital experiment in order to seek the couplings of rotor spin to Earth spin and rotor spin to rotor orbit [9]. As pointed out by Zhang *et al.* [10], however, the mechanical gyroscope spin is essentially different from the intrinsic spin of elementary particles. In fact, an extended body could have two different types of motion, i.e., orbit motion (the motion of the center-of-mass) and rotation. Thus an extra force (or force moment), which could come from the spin-spin (i.e., rotation-rotation) coupling between rotating macroscopic bodies, might change the three types of motion for the rotating bodies: (i) spin precession (i.e., a change of spin direction), (ii) a change of the rotation rate, and (iii) a change of the motion of the center-of-mass. It is known that general relativity (GR) only predicts (i), i.e., spin precession, while any possible connections of GR with (ii) and (iii) are now still open problems. Thus the Stanford GPB project simply includes a measurement of the spin precession rather than (ii) and (iii). In addition, although other gravitational theories, such as the gauge theories of gravitation with torsion [11], seem to include spin-spin coupling of fluid, it is difficult to discuss the spin-interaction between rotating rigid balls within the framework of these theories. For this reason, Zhang *et al.* recently developed a phenomenological model for the rotation-rotation interaction between the rotating rigid balls [10], which predicts (iii), i.e., the effect of the coupling, gyroscope spin to Earth spin, on the orbital acceleration of the gyroscope free-falling in Earth's gravitational field. In this sense this type of spin-spin coupling would violate the equivalence principle (EP) for the free-fall gyroscopes.

EP, as one of the fundamental hypotheses of Einstein's general relativity, has been tested by many experiments [12–18]. Recently, some different tests of EP for gravitational self-energy [19] and spin-polarized macroscopic objects [20,21] have been reported. However, in all of the experiments as well as the Satellite Test of the Equivalence Principle (STEP) and the Galileo Galilei (GG) space projects as well as the MICROSCOPE space mission [22–24], it is nonrotating bodies that are used. In addition, as pointed out above, although a gyroscope is used in the Stanford GPB project, only the precession of the gyroscopic spin is to be observed, which is irrelevant to the orbital motion.

Some relevant experiments have been performed by use of mechanical gyroscopes and give contradictory results [25–30]. In particular, the observations in these experiments were made by means of beam balance, and so only the gravity and its reacting force were working, which is irrelevant to inertial force. Therefore, this type of experiment is simply a test of statics independent of EP.

Recently, Hayasaka *et al.* investigated the effect of a rotating gyroscope on the fall-acceleration by comparing the fall-times of the gyroscope with differential rotating sense using the time-counter combined with three couples of the laser emitters and receivers [31]. Their experimental data show that the gravity acceleration of the right-rotating rotor at 18 000 rpm is smaller than that of the non-rotating one at the relative level of 10^{-4}, and the gravity acceleration of the

*Email address: junluo@public.wh.hb.cn

†Email address: yzhang@itp.ac.cn

‡Mailing address of Y. Z. Zhang.

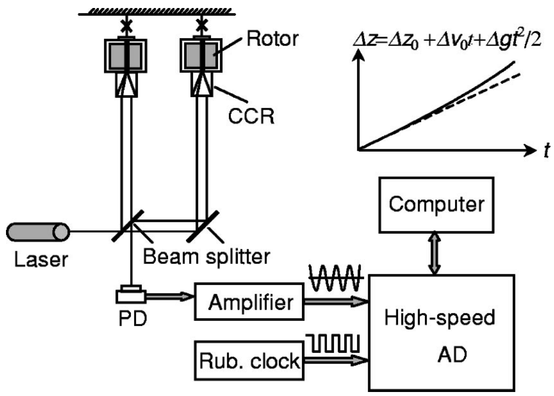

FIG. 1. Schematical diagram of a free-fall interferometer used to measure the differential acceleration between two gyroscopes with differential rotating senses.

left-rotating rotor is almost identical with that of the nonrotating (i.e., an asymmetric coupling). But the phenomenological theory for rotating rigid balls in Ref. [10] predicts a symmetric spin-spin coupling which is in the order of 10^{-14}, much less than the observation in Ref. [31]. As pointed out above, this type of free-fall experiment is a test of dynamics, which is closely related to EP. And hence, it is necessary to do a new dynamic test of EP by use of free-fall gyroscopes.

In this article, we shall report a new dynamic test of the spin-spin coupling between a gyroscope and the Earth. Based on the theoretical model in Ref. [10], a dimensionless parameter representing the strength of violation of EP can be defined as follows:

$$\eta_s = \frac{\Delta g}{g} = \kappa \left(\frac{\vec{S}_1 \cdot \vec{S}_e}{G m_1 M_e R_1} - \frac{\vec{S}_2 \cdot \vec{S}_e}{G m_2 M_e R_2} \right), \tag{1}$$

where G is the Newtonian gravitational constant, m_1, m_2, and M_e are the masses of the two gyroscopes and the Earth, respectively, and $\vec{S}_1$, $\vec{S}_2$, and $\vec{S}_e$ are their spin angular momenta correspondingly, R_1 and R_2 are the distances between the centers of the two gyroscopes and the Earth, respectively, and the parameter κ represents the universal coupling factor for the spin-spin interaction. Therefore, in a double free-fall (DFF) experiment, in which two gyroscopes with differential rotating senses drop freely, an observed nonzero value of η_s would imply violation of the EP or existence of spin-spin force between the gyroscope and the Earth.

II. EXPERIMENTAL DESCRIPTION

The schematic diagram of the DFF experiment is shown in Fig. 1. A frequency-stabilized He-Ne laser beam (633 nm) with the relative length standard of 1.3×10^{-8} is split by two beam splitters and sent vertically to the two corner-cube retroreflectors (CCRs) fixed on the bottoms of the test masses, respectively, and then combined again and forms interference fringes on a 12-ns-response-time photodiode (RS, Ltd., OSD15-5T). The differential vertical displacement of both test masses, the gyroscopes with differential rotating senses, is continuously monitored by the interferometer and sampled by means of a 10 MHz data-acquisition card (Gage, Ltd., Cs1250) combined with an external rubidium atomic clock (SRS, Inc., SR620), which provides a relative time standard of 10^{-10}, and then stored in a computer. The test masses are freely dropped in two 12-m-high vacuum tubes of about 20–50 mPa. Compared with the SFF experiment employed by Hayasaka *et al.*, the DFF scheme can minimize the environmental noises such as the tides, gravity gradient, seismic noise, and air damping and so on, because the differential mode design can suppress some common errors of both falling objects.

As we know, the sensitivity of such a Galilean experiment in which both dropping objects are put side-by-side is limited by the alignment of the beam propagation away from the vertical line [17]. For example, an error in the verticality of 5″ will contribute an uncertain differential acceleration of 0.3 μGal (1 Gal=1 cm/s^2). A proposed method to reduce this error is to locate the dropping masses directly one above the other, but the design and operation would be very complicated. However, in order to test the asymmetrical gravity acceleration effect of 10^{-4} as reported by Hayasaka *et al.*, the side-by-side setup is employed here, and the two test masses are separated horizontally (south-north) by 480 mm. This design is very convenient for us to drive the gyroscopes and release them.

Each of the two test masses consists of a steel gyroscope with a mass of 420.0 ± 2.5 g, a diameter of about 55 mm and a height of about 32 mm, a CCR of 76.4 ± 0.4 g and a diameter of 40 mm as well as an outer aluminum frame of 159.4 ± 0.9 g. Tinned copper wires with a diameter of 0.25 mm are used to suspend the test masses and melt by an instantaneous large current (>150 A) provided by a capacitor array, and then the test masses are released and drop freely [32]. A dc three-phase motor is used to drive one of the gyroscopes, and the other is in non-rotating status. The rotating speed of the gyroscope can be adjusted by changing the input voltage of the motor. Simultaneous measurement of the driving frequency of the motor and the rotating rate of the gyroscope rotor in a vacuum container of about 3 Pa showed that the rotating frequency of the rotor is equal to that of the motor with an uncertainty of 1%. It is useful for recording the rotating speed of the gyroscope without adding an external measurement system in the vacuum chamber. The rotating speed of the gyroscope is kept at (17000 ± 200) rpm. A mechanical claw is used to grasp the test mass during the speedup progress of the gyroscope, and it is then loosed when the gyroscope runs normally. The free-fall test masses are captured by two 1.2-m-length tubes with an assembly of thin rubber rings and aluminum foils, respectively. Because of the lack of a return mechanism, which could reset the dropping objects under the vacuum condition, we have to open the vacuum tubes after each free-fall measurement.

The diameter of the laser beam is kept in a range of 3.0–3.2 mm by a two-lens collimation assembly during 20 m optical length so that the beam wavefront effect can be neglected here. The differential radiation pressure on the test masses is less than 3×10^{-4} μGal for 0.5 mW laser power used here. The angles of the beam aligned with the local vertical are monitored by a telescope combined with two horizontal oil references, and then fed back to align the beam splitters by four fine screws. The aligned verticality is kept within 50″ for each laser beam; the maximum uncertainty of the differential acceleration due to the aligned verticality is 30 μGal.

The test mass with a nonrotation rotor is released about 3 ms before the other with a left- or right-rotating rotor in order to obtain an interference fringe rate of about 100 kHz by means of two differential relay switches. The amplitude spectrum of the seismic noise in our laboratory is about $10^{-9}/(f/\mathrm{Hz})^2\ \mathrm{m}/\sqrt{\mathrm{Hz}}$ [33], which will contribute an uncertainty of about 1 μGal to the final experiment result.

The sample data in each free-fall are processed as in the following steps. First, the dc offset and the amplitude of each interference fringe are determined from the original time-voltage data $\{t_i,V_i\}$. Second, by calculating an inverse function of the fringe using the dc offset and the amplitude determined, we can transform the data $\{t_i,V_i\}$ into the time-differential displacement data $\{t_i,\Delta z_i\}$. Finally, the data $\{t_i,\Delta z_i\}$ are fitted by a parabolic trajectory perturbed with a linear vertical gravity gradient γ. The differential displacement between both test masses is given by the equation as follows:

$$\Delta z=\Delta z_0+\Delta v_0 t+(\Delta g+\gamma\Delta z_0)t^2/2+\Delta v_0\gamma t^3/6, \quad (2)$$

where unknown parameters $\Delta z_0,\Delta v_0=g\Delta t_0$, and Δg are the initial differential vertical displacement, velocity, and acceleration at the same height, respectively. It is evident that the initial differential displacement, which includes their original suspending difference and descent height due to the release time delay Δt_0, has to be measured accurately. Here the suspending height difference of both test masses is less than 1 mm, and their descent height due to 3 ms delay is about 50 μm. In this case, the vertical gravity gradient effect is about 0.3 μGal. In addition, it is noted that the fitting initial time difference, which is here defined as the time difference of the fitting initial data away from the real release time of the latter test mass, will contribute an uncertain acceleration difference due to the coupling between the initial differential velocity and the vertical gravity gradient. In general, the fitting initial time difference should be kept below 0.1 s for 1 μGal uncertainty.

A known systematic error due to the finite speed of light is given by [34]

$$\Delta g/g\simeq 3\Delta v_0/C, \quad (3)$$

and the correction is about 0.3 μGal in our experiment. Another systematic error due to residual gas drag could be calculated as follows [35]:

$$\Delta g/g=A\Delta v_0 p\sqrt{8\mu/(\pi RT)}/(4mg), \quad (4)$$

where A ($\approx$170 cm^2) is the total surface area of the test mass, μ and R are the molecular weight of residual gas and the gas constant, m is the mass of the falling object, T is the temperature, and p is the residual pressure. The uncertain acceleration due to the drag effect is less than 5 μGal at $p=50$ mPa and $T=300$ K.

Variation of the magnetic flux density is within 0.1 G near the right-, left-, or nonrotating rotor, and the geomagnetic flux density is about 0.4 G here. The estimation shows that the effect of the geomagnetic field on the steel rotor is at the level of 10^{-10} Gal.

An acceleration difference due to interaction between a possible horizontal velocity difference Δv_h and rotation of the Earth is given by

$$\Delta g=2\Delta\vec{v}_\mathrm{h}\times\vec{\Omega}\leqslant 2\Delta v_\mathrm{h}\Omega\cos\lambda, \quad (5)$$

where Ω is the angular frequency of the Earth's rotating, and λ ($\simeq$30°) is the latitude of our laboratory. The Δv_h is estimated smaller than 4.3 mm/s according to interference intensity of the two interference beams reflected from the CCRs versus the falling length (6 mm deviation for 10-m-fall height). Therefore, the uncertain acceleration due to the procession effect is less than 54 μGal. It means that the horizontal velocity difference would have to be monitored in the further experiment with a higher precision.

A possible lifting force for a rotating rotor due to the residual gas flow's circulation can be calculated based on the Zhukovskii theorem as follows [36]:

$$\vec{F}_\mathrm{lift}=m\vec{a}_\mathrm{lift}=-2\rho_\mathrm{gas}\vec{V}\times\vec{\omega}, \quad (6)$$

where $\vec{V}$ is the velocity of the rotating rotor, $\vec{\omega}$ ($\sim$17000 rpm) is the angular velocity of the rotating rotor, and ρ_gas is the residual gas density in the vacuum tube. Because the interferometric measurement here is nearly insensitive to the horizontal motions of the two test masses, the lifting effect on the vertical acceleration difference would be zero if $\vec{\omega}$ was exactly along the vertical axis. The maximum uncertain rotation direction of the rotating rotor away from the vertical axis is estimated within 2.4 mrad, thus a possible vertical acceleration difference between the rotors due to the gas flow's lifting is at the level of 10^{-10} Gal, which can be neglected here.

III. EXPERIMENTAL RESULTS

A typical voltage output from the photodiode is shown in Fig. 2. Figure 2(a) is the intensity curve of the interference fringe as the first dropping object (nonrotating here) is released, and the rate of the fringe increases with the falling of the nonrotating test mass until the other is also released. As both test masses drop freely, the rate of the fringe is modulated by their acceleration difference or the noises, as shown in Fig. 2(b).

Figure 3 lists 3 sets of 5 measurements each of N-L, N-R, and N-N, where L, R, and N represent left-, right-, and nonrotating, respectively. The uncertain differential acceleration of each free-fall comes to the level of 1000 μGal, while the fitting standard deviation ($\pm 1\sigma$) is only a few μGal, but it is noted that the uncertainty is independent of their rotating senses. Statistical result shows that relative uncertainty of the differential acceleration between the nonrotating and left-rotating test masses is $\Delta g_\mathrm{N\text{-}L}/g=(0.90\pm 0.94)\times 10^{-6}$, and that between the nonrotating and right-rotating is $\Delta g_\mathrm{N\text{-}R}/g$

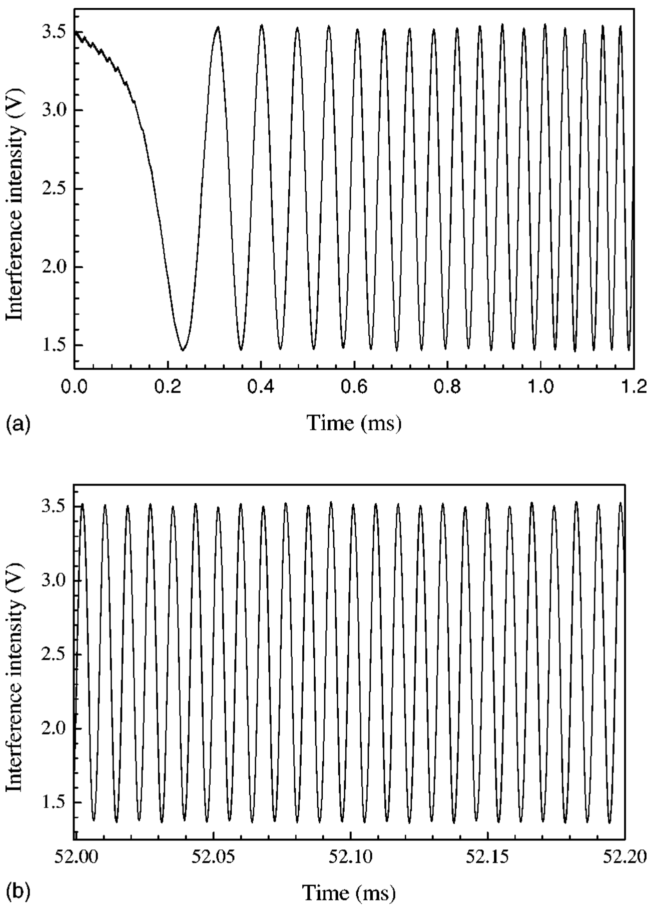

FIG. 2. (a) Interference fringe intensity as the first test mass is released. The fringe rate increases with its falling; (b) interference fringe intensity as both the test masses drop freely.

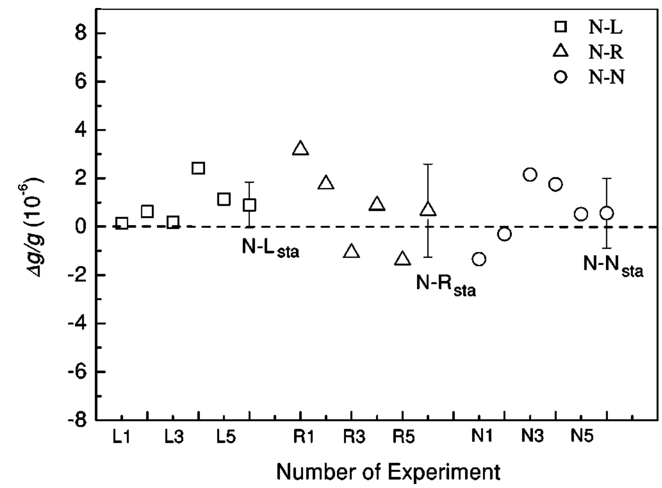

FIG. 3. Statistical result of the relative differential acceleration between two test masses with different rotating senses. L, R, and N represent left, right-, and nonrotating, respectively, $L_{\rm sta}$, $R_{\rm sta}$, and $N_{\rm sta}$ represent the statistical values of the corresponding differential acceleration, and the error bars denote $\pm 1\sigma$.

$=(0.67\pm 1.92)\times 10^{-6}$. They are almost the same as the background limit of $\Delta g_{\rm N\text{-}N}/g=(0.56\pm 1.44)\times 10^{-6}$.

Summarizing the data obtained in Ref. [25], the weight loss, resulting from the mass reduction or the acceleration decrease, for right-rotating around the vertical axis is approximately formulated by Hayasaka and Takeuchi, in units of dynes, as follows:

$$\Delta W(\omega)=\alpha m r_{\rm eq}\omega, \tag{7}$$

where m is the mass of rotor (in g), ω is the angular frequency of rotation (in rad/s), and $r_{\rm eq}$ is the equivalence radius (in cm), defined as follows:

$$m r_{\rm eq}=\int\int \rho(r,z) 2\pi r^2\, dr\, dz, \tag{8}$$

where $\rho(r,z)$ is the density of the rotor materials. Their experimental result shows that the factor α is about 2×10^{-5}/s. Considering the generalization of the possible anomalous weight change of the rotating gyroscopes, the possible weight loss of the two rotating directions of the gyroscope could be given as follows [29,37]:

$$\Delta W(\omega)=\beta I\omega, \tag{9}$$

where I is the inertia moment of the rotating rotor; β could be considered as a factor dependent upon the anomalous effect. Based on the above formulas, all reported experimental tests of the anomalous effect are tabulated in Table I as sug-

TABLE I. Summary of test experiments of anomalous weight change of the rotating rotors.

Experiment	Method	M (g)	D (cm)	$r_{\rm eq}$ (cm)	I (g cm^2)	$\omega_{\max}$ (rpm)	ΔW (dyn)	α (s^{-1})	β (cm^{-1} s^{-1})
Hayasaka & Takeuchi	BB	140	5.2	1.85[a]	473[b]	13000	7.6	2.14×10^{-5}	1.17×10^{-5}
		175	5.8	2.26[a]	736[b]		11.7	2.17×10^{-5}	1.16×10^{-5}
Faller *et al.*	BB	451	5.1	1.70[b]	1466[b]	6000	<0.39	$\leqslant 8.14\times 10^{-7}$	$\leqslant 4.25\times 10^{-7}$
Quinn & Picard	BB	330	4.0	1.33[b]	660[b]	8000	<0.06	$\leqslant 1.60\times 10^{-7}$	$\leqslant 1.06\times 10^{-7}$
Nitschke & Wilmarth	BB	142	3.84	1.28[b]	328[a]	22000	<0.07	$\leqslant 1.64\times 10^{-7}$	$\leqslant 0.91\times 10^{-7}$
Imanishi *et al.*	BB	129	5.0	1.94[a]	551[a]	11000	<0.32	$\leqslant 1.12\times 10^{-6}$	$\leqslant 5.10\times 10^{-7}$
Hayasaka *et al.*	SFF	175	5.8	1.93[b]	970[a]	18000	24.9	3.90×10^{-5}	1.36×10^{-5}
Luo *et al.*	DFF	420	5.49	1.83[b]	1582[b]	17000	<0.80	$\leqslant 5.89\times 10^{-7}$	$\leqslant 2.86\times 10^{-7}$

[a]Data provided by the corresponding reference.
[b]Data calculated according to the assumption of a uniform composition rotor.

gested by Newman [38]. It is noted that some unknown parameters are calculated according to a uniform composition rotor assumption.

From the results of our DFF experiment, there is no apparent differential acceleration between the rotating and nonrotating test masses within our experimental limits. Therefore, we can conclude that the differential acceleration between the rotating and nonrotating gyroscopes is almost 2 orders of magnitude smaller than reported in Ref. [31], and the differential acceleration effect between the right- and left- versus the nonrotating was not observed in our experiment at the relative level of 2×10^{-6}. It means that EP is still valid for extended rotating bodies, and the spin-spin interaction between the rotating extended bodies has not been observed at this level. And then, according to Eq. (1) and the approximately uniform sphere mode of the Earth, it can be concluded that $\kappa\leqslant2\times10^{-18}$ kg^{-1}, which sets an upper limit for the spin-spin interaction between a rotating extended body and the Earth.

IV. DISCUSSION

A large limitation in our experiment comes from the friction coupling between the rotating rotor and the frame of the test mass. The friction coupling not only causes a high-frequency mechanical vibration of the CCR at the frequency of the rotating rotor, but also results in a slowly rotating motion of the frame, which frequency is about 1 Hz. Another main limitation had been proved to come from the outgassing effect of the vacuum pump with a full rated pumping speed 1500 L/s due to the asymmetrical outgassing for the two tubes here. It is hoped that the sensitivity of our DFF experiment could be improved by one or two orders in the near future, and the upper limit of the dependent factors α or β could be improved to 10^{-9}. Therefore, the new EP for the rotating extended bodies could be tested at the same level correspondingly.

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