A Mass-Energy United Test of the Equivalence Principle

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The equivalence principle (EP) is one of the basic assumptions of general relativity. Almost all new theories\textsuperscript{1} that attempt to unify gravity with the standard model\textsuperscript{2} require the EP be broken. Experimental tests of EP provide opportunities for verification of different theoretical models and emergence of new physics. Traditional mass tests\textsuperscript{3-9} of EP have achieved the precision of $10^{-15}$ level\textsuperscript{3}. Tests with quantum properties including spin\textsuperscript{10,11}, superposition\textsuperscript{12}, quantum statistics\textsuperscript{10} and internal state\textsuperscript{4,13}, have been performed, and entanglement\textsuperscript{14} test was also proposed. Energy is another very important property and is related to mass by the mass-energy equivalence (MEE). However, mass-energy united tests of EP have never been carried out. Here, we achieve for the first time the united EP test covering energy interval from micro-eV to giga-eV by a mass and internal energy specified atom interferometer (AI). The AI was realized by taking advantage of the Four-Wave Double-diffraction Raman transition (4WDR) method\textsuperscript{7} for specified internal energy states, and by extending 4WDR to include excited states. The Eötvös parameters of the four paired combinations ($^{87}\text{Rb}|F=1\rangle-^{85}\text{Rb}|F=2\rangle$, $^{87}\text{Rb}|F=2\rangle-^{85}\text{Rb}|F=2\rangle$, $^{87}\text{Rb}|F=1\rangle-^{85}\text{Rb}|F=3\rangle$ and $^{87}\text{Rb}|F=2\rangle-^{85}\text{Rb}|F=3\rangle$) were measured to be $\eta_1=(1.5 \pm 3.2) \times 10^{-10}$, $\eta_2=(-0.6 \pm 3.7) \times 10^{-10}$, $\eta_3=(-2.5 \pm 4.1) \times 10^{-10}$ and $\eta_4=(-2.7 \pm 3.6) \times 10^{-10}$.

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respectively. The violation parameters of mass and internal energy are constrained to

\[ \eta_0 = (-0.8 \pm 1.4) \times 10^{-10} \text{ and } \beta = (-0.6 \pm 6.9) \times 10^{-5} \].

This work opens a door for united tests of EP and MEE in large energy range with quantum systems.

Mass tests of EP have been performed in different ways including Lunar laser ranging\(^{15}\), torsion balance\(^{16,17}\), satellite\(^3\) and AIs\(^{4-9}\). However, it is unknown whether the energy behaves the same as mass in a gravitational field although MEE holds at least at \(10^{-7}\) level\(^{18}\). To parameterize possible contributions of mass and energy to EP violation, under the condition that MEE is valid, we express the gravitational mass \(m_g\) of a test body as a sum of different types of mass-energy and their EP violation terms\(^1\)

\[
m_g = \sum_A \left(1 + \eta^A\right) \frac{E^A}{c^2} 
\]

\[= m_i + \sum_A \eta^A \frac{E^A}{c^2}, \quad (1)\]

where \(m_i = \sum_A \frac{E^A}{c^2}\) is the inertial mass, \(A\) labels different interactions, \(E^A\) are their corresponding energies, \(c\) is the speed of light, and \(\eta^A\) are EP violation parameters. If EP validates, then \(\eta^A = 0\). Up to now, EP tests using macro objects did not apparently involve energy. Only with microscopic particles as test bodies can it be possible to do energy dependent test of EP by selecting internal states of the particles. The early microscopic particle-based EP test was done by neutron interferometers\(^{19,20}\). In recent years, with the development of atomic manipulation technology, Atom-based quantum test of EP has become possible. As listed in Table 1, mass tests with atoms have been performed using \(^{85}\text{Rb}-^{87}\text{Rb}, \quad ^{87}\text{Rb}-^{39}\text{K} \) and \(^{88}\text{Sr}-^{87}\text{Sr}\) atom pairs \(^{4-9,10}\). Beyond-mass tests have been investigated using different quantum properties including quantum statistics\(^{10}\), spin\(^{11,12}\), superposition\(^{12}\) and internal state\(^4,13\). However, these experiments obtained either the mass violation coefficient or the energy violation coefficient. Up to now, no one has combined
mass and energy in one platform to precisely extract potential tiny difference between mass and energy violation coefficients in noisy environments. The main obstacles lie in the technical complexity when putting dual-species atoms and specific quantum states together in AIs. It is rather difficult to satisfy the following requirements in one experiment: (1) keeping the same specified quantum state in an AI; (2) suppressing common mode noise for different species of atoms; (3) adjusting internal energy of atoms.

Here, we improve the 4WDR dual-species $^{87}$Rb-$^{85}$Rb AI and perform a united mass and internal energy test of EP. Mass and internal energy specified AIs are realized by deterministically manipulating the internal states of $^{87}$Rb and $^{85}$Rb atoms. Eötvös parameters are measured for the four paired combinations, constraints to mass and energy violation are then given respectively (see Table 1).

### Table 1 | Measured Eötvös parameters of EP tests with atoms.

| Mass Pair | $F$-$F'$ | Mass Test | Beyond-Mass Test | Ref. |
|-----------|----------|-----------|------------------|-----|
| $^{85}$Rb-$^{87}$Rb | 2-1 | $\eta = (1.2 \pm 1.7) \times 10^{-7}$ | - | 4 |
| $^{85}$Rb-$^{87}$Rb | mixed | $\eta = (1.2 \pm 3.2) \times 10^{-7}$ | - | 5 |
| $^{39}$K-$^{87}$Rb | mixed | $\eta = (0.3 \pm 5.4) \times 10^{-7}$ | - | 6 |
| $^{85}$Rb-$^{87}$Rb | 2-1 | $\eta = (2.8 \pm 3.0) \times 10^{-8}$ | - | 7 |
| $^{39}$K-$^{87}$Rb | mixed @ 0g | $\eta = (0.9 \pm 3.0) \times 10^{-4}$ | - | 8 |
| $^{39}$K-$^{87}$Rb | mixed | $\eta = (-1.9 \pm 3.2) \times 10^{-7}$ | - | 9 |
| $^{39}$K-$^{87}$Rb | 9/2-0 | $\eta = (0.2 \pm 1.6) \times 10^{-7}$ | $k = (0.5 \pm 1.1) \times 10^{-7}$ | 10 |
| $^{87}$Rb | 2-3 | - | $\eta = (0.4 \pm 1.2) \times 10^{-7}$ | 4 |
| $^{87}$Rb | $m_F = \pm 1$ | - | $\eta = (1.2 \pm 3.2) \times 10^{-7}$ | 11 |
| $^{87}$Rb | 1-2 | - | $\eta = (1.4 \pm 2.8) \times 10^{-9}$ | 12 |
| $^{87}$Rb | 1-1@2 | - | $\eta = (3.3 \pm 2.9) \times 10^{-9}$ | 12 |
| $^{87}$Rb | 1-2 | - | $\eta = (0.9 \pm 2.7) \times 10^{-10}$ | 13 |

| Mass Pair | $F$-$F'$ | Mass-Energy Test |
|-----------|----------|-----------------|
| $^{87}$Rb-$^{85}$Rb | 1-2 | $\eta_1 = (1.5 \pm 3.2) \times 10^{10}$ |
| $^{87}$Rb-$^{85}$Rb | 2-2 | $\eta_2 = (-0.6 \pm 3.7) \times 10^{10}$ |
| $^{87}$Rb-$^{85}$Rb | 1-3 | $\eta_3 = (-2.5 \pm 4.1) \times 10^{10}$ |
| $^{87}$Rb-$^{85}$Rb | 2-3 | $\eta_4 = (-2.7 \pm 3.6) \times 10^{10}$ |
| | | $\eta_0 = (-0.8 \pm 1.4) \times 10^{10}$ |
| | | $\beta = (-0.6 \pm 6.9) \times 10^{5}$ |

In this experiment, we use $^{87}$Rb and $^{85}$Rb atom pairs with hyperfine levels, see Fig.1 (a). Then Eq. (1) is rewritten as (Extra Data Eq.(s1)).
where $\alpha^{87}$ and $\alpha^{85}$ are the mass violation parameters of $^{87}\text{Rb}$ and $^{85}\text{Rb}$ atoms respectively, $\beta$ is the internal energy violation parameter. $\Delta E$ is the internal energies (the difference of two hyperfine levels). The kinetic energy difference of atoms with a velocity of 2.5 m/s in the interference process is only less than 0.06 $\mu$eV. We assign different mass violation parameters to account for the different composition and complex interactions within each element. The EP violation between two test bodies is described by Eötvös parameter $\eta$.

Inserting Eq. (2) into Eq. (3), taking the denominator approximately equal to 1, we get the Eötvös parameters of the four paired combinations as,

$$\eta_j = \eta_0 + \beta \chi_j,$$

where $\eta_0 = \alpha^{87} - \alpha^{85}$, $\chi_j$ ($j = 1, 2, 3, 4$) = (0, -1.6 × 10^{-16}, 3.5 × 10^{-16}, 1.9 × 10^{-16}) are scaled internal energy coefficients.

We proposed and implemented a 4WDR scheme (Fig. 1(a)) in our previous EP test, the 4WDR dual-species AI owns advantages of symmetrical-recoil double-diffraction, common mode noise rejection and magic intensity ratio (MIR, it means the total ac Stark shift caused by Raman beams in dual-species Raman transitions is rejected to zero). However, the actual 4WDR AI needs to apply a blow away pulse to clear the remaining atoms in the middle path, as shown in the upper part of Fig. 1(b), which is not suitable for
preparing upper ground state (UGS) ($^{87}$Rb|F=2 or $^{85}$Rb|F=3) AI. To prepare UGS AI, as shown in the lower part of Fig. 1(b), an additional $\pi$-blow away pulse sequence is applied to prepare initial state and to select narrow velocity atoms, and a repumping pulse is added to make the intermediate path atoms deviate from the interference loop. At the end of interference, a blow away pulse is used to clear UGS atoms and a repumping pulse is used to pump atoms to UGS for high contrast detection. In addition, to ensure the synchronization of the dual-species atoms and reduce the systematic error, a $\pi$-blow away-state selection-repumping pulse sequences for the preparation of the initial state and speed selection are added to the lower ground state (LGS) ($^{87}$Rb|F=1 or $^{85}$Rb|F=2) AI, as shown in the upper part of Fig. 1(b). By doing this, the 4WDR is extended to be applicable to both LGS and UGS, which is called 4WDR-e scheme hereafter. In the experiment, the composition of the state selection pulses will be different for different atom pairs. The specific timing of the four combinations is detailed in Extra Data Fig. 1.
Fig. 1 | Schematic diagram of 4WDR-e $^{87}$Rb-$^{85}$Rb dual-species AI. (a) Relevant sub-levels covering energy interval from micro-eV to giga-eV. Raman lasers with frequencies of $\omega_1$, $\omega_2$, and $\omega_3$ are used for $^{85}$Rb atoms, while that with frequencies $\omega_1$, $\omega_2$, and $\omega_4$ are for $^{87}$Rb atoms; $\delta_1$ is the detuning of $\omega_1$, $\delta_2$ is the detuning of $\omega_2$. $\omega_1$ and $\omega_2$ are detuned to the blue side of transitions $^{85}$Rb$|F = 3\rangle$ to $|F' = 4\rangle$ with a detuning of $\Delta_1$ and $^{87}$Rb$|F = 2\rangle$ to $|F' = 3\rangle$ with a detuning of $\Delta_2$. (b) The 4WDR-e configuration for $^{87}$Rb-$^{85}$Rb dual-species AI. The blue dash lines represent LGS atoms, and red solid lines represent UGS atoms. (c) Experimental setup. PM: polarization maintaining; 3D-MOT: three-dimensional magneto-optical trap.

The experimental setup is shown in Fig. 1(c), which it is upgraded from that in our previous work. It is briefly described as follows. The three-dimensional magneto-optical trap (3D-MOT) of the lower part of the fountain is (0, 0, 1) configuration. The piezoelectric ceramic mounted mirror is for scanning the angle of the Raman lasers and compensating the Coriolis effect. A time-division-multiplexing method is used to couple multiple laser beams in one fiber. A group of Raman beams ($\omega_1$, $\omega_3$, and $\omega_4$) propagate downward through the top window of the vacuum chamber. Another group of Raman beams ($\omega_2$, $\omega_3$, and $\omega_4$) propagate upward through the bottom window of the vacuum chamber. An active compensation is used to the magnetic field shield to further reduce fluctuation of the magnetic field. The fluorescence of $^{87}$Rb and $^{85}$Rb atoms is alternately collected by detector A and B to reduce errors caused by inconsistence of the detectors.

The statistical uncertainty is improved by improving atom numbers, compensating rotation of the Earth, increasing stability and free evolution time. To increase the signal to noise ratio and to suppress systematic errors, the $z$-direction effective temperature of the atoms participating in interference is lowered to 400 nK by selecting velocity group. The long-term system stability is improved by optimizing optics. The evolution time $T$ among $\pi/2$-$\pi$-$\pi/2$ Raman pulses is carefully adjusted to 203.164 ms to minimize ellipse-fitting error. The improvement footprint of Allan deviations of $\eta$ measurements using $^{87}$Rb$|F = 1\rangle$-$^{85}$Rb$|F = 2\rangle$ dual-species AI is shown in Extended Data Fig. 2.
Fig. 2 | Experimental data. (a) Experimentally measured \( \eta \) values, where the error corresponding to the effective wave vector is corrected. (a1), (a2), (a3) and (a4) are measurements for \( \eta_1 \), \( \eta_2 \), \( \eta_3 \) and \( \eta_4 \), respectively. (b) Allan deviation of \( \eta_1 \) (red squares), \( \eta_2 \) (black dots), \( \eta_3 \) (green boxes) and \( \eta_4 \) (blue triangles). (c) Dependence of \( \eta \) values on energy, the intercept value of the fitted straight line \( \eta_0 = (-0.8 \pm 1.4) \times 10^{-10} \), and the slope value \( \beta = (-0.6 \pm 6.9) \times 10^5 \).

The experimental data for four combination pairs are shown in Fig. 2. Fig. 2(a1) shows 640 measurements of \( \eta_1 \) value using \( ^{87}\text{Rb}\vert F=1 \rangle - ^{85}\text{Rb}\vert F=2 \rangle \) atom pair, where each measurement is given by ellipse fitting (with free evolution time of 203.164 ms and
measurement time of 280 s for two detectors). The average value of these measurements is 2.5 × 10^{-10}. Fig. 2 (a2), (a3) and (a4) show 512 measurements of $\eta_2$, $\eta_3$ and $\eta_4$ using $^{87}\text{Rb}|F=2\rangle - ^{85}\text{Rb}|F=2\rangle$, $^{87}\text{Rb}|F=1\rangle - ^{85}\text{Rb}|F=3\rangle$ and $^{87}\text{Rb}|F=2\rangle - ^{85}\text{Rb}|F=3\rangle$ atom pairs, respectively.

The Allan deviations are shown in Fig. 2(b). The red squares are data of $\eta_1$, the statistical uncertainty is 0.6 × 10^{-10} at an average time of 35840 s. The black dots, green boxes, and blue triangles are data of $\eta_2$, $\eta_3$ and $\eta_4$, respectively. The corresponding statistical uncertainties at an average time of 17920 s are 1.8 × 10^{-10}, 2.5 × 10^{-10} and 1.8 × 10^{-10}, respectively.

The systematic errors are suppressed by correcting the wave vector, optimizing MIR, compensating the rotation of the Raman beams mirror, calibrating the gravity gradient error, the quadratic Zeeman shift and suppressing the wave-front error.

The uncertainty of wave vectors is suppressed to 0.5 × 10^{-10} by precise frequency control. The MIR is optimized from 1.0: 1.0: 3.1: 14 in our previous experiment to 1.00: 3.05: 14.3 (Extra Data Fig.3). By improving the laser intensity control accuracy, the ac Stark shift is evaluated by modulating the intensity of the Raman lasers, the final ac Stark shift are evaluated as $\Delta \eta_1 = (0.1\pm 0.2) \times 10^{-10}$ (Extra Data Fig.4). The ac Stark shift of other three combination pairs are evaluated as $\Delta \eta_2 = (0.4 \pm 0.8) \times 10^{-10}$, $\Delta \eta_3 = (0.0 \pm 0.2)$ $\times 10^{-10}$, $\Delta \eta_4 = (-0.1 \pm 0.2) \times 10^{-10}$. The Coriolis error is suppressed by optimizing atom cloud coincidence and compensating the rotation of the Raman beams mirror, the Coriolis effect is suppressed to -0.1 × 10^{-10} with an uncertainty of 0.4 × 10^{-10}. To decrease the difference of positions and velocities of two atom clouds, the gravity gradient phase shift is calibrated by adjusting the background magnetic field of the magneto-optical trap (MOT), the laser frequency detuning of moving molasses. The phase shift caused by position difference is 3.6 × 10^{-10}/mm (Extra Data Fig.5), the uncertainty corresponding
gravity gradient is calibrated as $2.8 \times 10^{-10}$ by precise control of the position. The quadratic Zeeman shift is calibrated by modulating magnetic field. The magnetic field contribution to $^{87}\text{Rb}|F=1\rangle-^{85}\text{Rb}|F=2\rangle$ is $\Delta \eta_1 = (0.5 \pm 0.3) \times 10^{-10}$ (Extra Data Fig.6), and that for $^{87}\text{Rb}|F=2\rangle-^{85}\text{Rb}|F=3\rangle$, $^{87}\text{Rb}|F=2\rangle-^{85}\text{Rb}|F=2\rangle$, and $^{87}\text{Rb}|F=1\rangle-^{85}\text{Rb}|F=3\rangle$ are evaluated as $\Delta \eta_2 = (1.3 \pm 0.8) \times 10^{-10}$, $\Delta \eta_3 = (-1.3 \pm 0.8) \times 10^{-10}$, and $\Delta \eta_4 = (-0.5 \pm 0.3) \times 10^{-10}$ respectively.

The wave-front-aberration error is analyzed and estimated by modulating the size of detection beams. The error and uncertainty of the wave-front aberration analyzed from the actual experimental parameter is $(0.5 \pm 0.5) \times 10^{-10}$ (Extra Data Fig.7).

The contribution of other systematic error terms is evaluated less than $1.0 \times 10^{-10}$.

The final data of Eötvös parameters are shown in Fig. 2(c), fitting with Eq. (4) gives $\eta_0 = (-0.8 \pm 1.4) \times 10^{-10}$, $\beta = (-0.6 \pm 6.9) \times 10^5$. The error budget is summarized in Table 2.

| Parameters                | $\eta_1$ | $\eta_2$ | $\eta_3$ | $\eta_4$ | $\Delta \eta_1$ | $\Delta \eta_2$ | $\Delta \eta_3$ | $\Delta \eta_4$ |
|---------------------------|----------|----------|----------|----------|-----------------|-----------------|-----------------|-----------------|
| Experimental data         | 49438.1  | 49437.5  | 49431.8  | 49432.7  | 0.6             | 1.8             | 2.5             | 1.8             |
| Wave vector               | 49435.6  | 49436.0  | 49435.2  | 49435.6  | 0.5             | 0.5             | 0.5             | 0.5             |
| ac Stark shift            | 0.1      | 0.4      | 0.0      | -0.1     | 0.2             | 0.8             | 0.2             | 0.2             |
| Coriolis effect           | -0.1     | -0.1     | -0.1     | -0.1     | 0.4             | 0.4             | 0.4             | 0.4             |
| Gravity gradient          | 0.0      | 0.0      | 0.0      | 0.0      | 2.8             | 2.8             | 2.8             | 2.8             |
| Quadratic Zeeman shift    | 0.5      | 1.3      | -1.3     | -0.5     | 0.3             | 0.8             | 0.8             | 0.3             |
| Wave-front aberration     | 0.5      | 0.5      | 0.5      | 0.5      | 0.5             | 0.5             | 0.5             | 0.5             |
| Others                    | 0.0      | 0.0      | 0.0      | 0.0      | 1.0             | 1.0             | 1.0             | 1.0             |
| Total                     | 1.5      | -0.6     | -2.5     | -2.7     | 3.2             | 3.7             | 4.1             | 3.6             |

To conclude, we have completed a united test of EP using mass and internal energy specified atoms in one experiment. We observed no violation of EP at $10^{-10}$ level in $\mu\text{eV-GeV}$ mass-energy range. Compared with the previous tests, this work gives the mass constraint parameter $\eta_0$ and energy constraint parameter $\beta$ simultaneously for the first time. This is also the first time to determine $\beta$. The current value of $\beta$ was obtained from a large
mass-energy gap experiment, it can be further improved by other mass-energy
experiments such as metastable alkaline earth AI at eV region. Meanwhile, $\beta$ in Eq.(4)
actually includes contribution of possible violation of MEE. With steady improvements of
AI technology, such as the application of high-sensitivity\textsuperscript{27} and long-baseline\textsuperscript{28}, united and
even quantum tests\textsuperscript{29,30} of MEE and EP will become possible in the future.

\textbf{Online Content}

Methods, along with additional Extended Data display items and Source Data, are
available in the online version of the paper; references unique to these sections appear
only in the online paper.

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contributed significantly to the early stages of the experiment. X.C., D.-F.G., M. L., Y.-Z.Z.

and W.-T.N. performed theoretical calculations. All authors read the manuscript. J.W. and

M.-S.Z. supervised the project.

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METHODS

EP formulation for rubidium atoms. Following Eq.(1) and Fig. 1 (a), for rubidium atoms, the inertial mass is equal to the sum of the mass of lower ground state (LGS) and the internal mass-energy,

\[ m_g = \left(1 + \alpha\right) \frac{E_{\text{LGS}}}{c^2} + \left(1 + \beta\right) \frac{\Delta E}{c^2} \]

\[ = m_i + \alpha m_0 + \beta \frac{\Delta E}{c^2} \approx (1+\alpha)m_i + \beta \frac{\Delta E}{c^2} \]  

where \( m_i \equiv \frac{E_{\text{LGS}}}{c^2} + \frac{\Delta E}{c^2} \) is the inertial mass, \( m_0 \equiv \frac{E_{\text{LGS}}}{c^2} \) is the rest mass of LGS, and \( \Delta E \equiv E_{\text{UGS}} - E_{\text{LGS}} \) is the internal energy which is the difference between LGS and UGS. \( m_i \approx m_0 \), because the internal energy (\( \approx \mu\text{eV} \)) is much smaller than the test mass (\( \approx \text{GeV} \)). Eq. (4) is expanded as follows,

\[
\begin{align*}
\eta_1 &= \eta_0 \\
\eta_2 &= \eta_0 \beta \epsilon^85 \\
\eta_3 &= \eta_0 + \beta \epsilon^87 \\
\eta_4 &= \eta_0 + \beta \left( \epsilon^87 - \epsilon^85 \right)
\end{align*}
\]

where \( \epsilon^87 \) and \( \epsilon^85 \) are dimensionless energy scaling factors.

\[ \epsilon^85 \equiv \frac{\Delta E^85}{m_{i0} c^2} = 1.6 \times 10^{-16} \]  

\[ \epsilon^87 \equiv \frac{\Delta E^87}{m_{i0} c^2} = 3.5 \times 10^{-16} \]

The 4WDR-e atom interferometry. As shown in Fig. 1(a), the frequencies of the Raman lasers satisfy the conditions:

\[ \omega_1 + \delta_1 = \omega_2 - \delta_2 = \omega_3 - 3.04 \text{ GHz} = \omega_4 - 6.83 \text{ GHz} \]
where $\delta_1$ and $\delta_2$ ($\delta_1 = -\delta_2$) are two-photon detunings of $\omega_1$ and $\omega_2$, respectively. The phase shift of dual-species AI is

$$\Delta \phi = \Delta k_{\text{eff}} g (T + 2\tau) T (1 + 4\tau / \pi T),$$

where $\Delta k_{\text{eff}}$ is the difference of effective wave vectors of the dual-species atoms, $\tau$ is the duration of the $\pi/2$ Raman pulses. As shown in Fig.3 (a) and (b) in Ref. [7], the ac Stark shift caused by Raman lasers can be eliminated by selecting the frequencies and optimizing the intensity ratio of the Raman lasers. The common-mode phase noise caused by shared $\omega_1$ and $\omega_2$ can be rejected. The phase noise of $\omega_3$ and $\omega_4$ are suppressed by double-diffraction Raman transition. The interference path in 4WDR AI is completely symmetrical, and the influence of the coupling between photon recoil and gravity gradient can be decreased to a large extent. In addition, the interference loop for one species atom keeps at the same internal state, thus the influence of different internal states is also reduced.

The 4WDR-e scheme is explained by taking $^{85}$Rb atoms as an example.

For LGS AI, the $\pi$-blow away-$\pi$-repumping pulses are added for states preparation and velocity-selection. The atoms in the interference loop are kept in $|F=2\rangle$ state by performing upward and downward recoil operations on the atoms at the same time. During coherent operation, the atoms remaining in the $|F=3\rangle$ state will affect the interference. Therefore, a blow away pulse is added to clear atoms in $|F=3\rangle$ state.

For UGS AI, the $\pi$-blow away pulses are added for states preparation and velocity-selection. After the atoms interact with the first $\pi/2$ pulse, they are transited from $|F=2\rangle$ to $|F=3\rangle$. A repumping pulse is used to pump the atoms from $|F=2\rangle$ to $|F=3\rangle$. Although this process cannot completely clean up the atoms in $|F=2\rangle$ state, it can make them only as background without participating in the interference process. Due to the
presence of a repumping pulse, the atom number in the background increases sharply. In
order to decrease the background, we use a blow away-repumping pulse sequence after the
last Raman $\pi/2$ pulse, and only detect the atoms in $|F=2\rangle$ state which participate in the
interference loop. Note that, when the detected state is inconsistent with the interference
state, a $\pi$ phase correction is required.

For dual-species AI with different atom pairs, atoms are initially prepared to states
$^{87}\text{Rb}|F=2\rangle$ and $^{85}\text{Rb}|F=3\rangle$. The additional pulse sequences can be arranged differently. The
specific pulse sequence for the four pairs is shown in Extended Data Fig. 1. These pulse
sequences are described in detail as follows.

(a) $^{87}\text{Rb}|F=1\rangle-^{85}\text{Rb}|F=2\rangle$ dual-species AI (Extended Data Fig. 1(a)). A $\pi$-blow
away-$\pi$-Repumping pulses sequence is applied to $^{87}\text{Rb}$ and $^{85}\text{Rb}$ for states preparation and
velocity-selection, after that atoms in states $^{87}\text{Rb}|F=2\rangle$ and $^{85}\text{Rb}|F=3\rangle$. Here, the $\pi$-pulse is
a weak single-diffraction Raman pulse, used to transfer narrow-velocity atoms. The blow
away pulse is used to clear the atoms residing in states $^{85}\text{Rb}|F=3\rangle$ and $^{87}\text{Rb}|F=2\rangle$, a
repumping pulse is applied for repumping atoms from $^{87}\text{Rb}|F=1\rangle$ and $^{85}\text{Rb}|F=2\rangle$ to
$^{87}\text{Rb}|F=2\rangle$ and $^{85}\text{Rb}|F=3\rangle$. A $\pi/2$-blow away-$\pi$-blow away-$\pi/2$ pulses sequence is applied
to realize $^{87}\text{Rb}|F=1\rangle-^{85}\text{Rb}|F=2\rangle$ dual-species AI. Here, the blow away pulse is used to clear
the $^{87}\text{Rb}|F=2\rangle$ and $^{85}\text{Rb}|F=3\rangle$ sate atoms residing in the middle-path.

(b) $^{87}\text{Rb}|F=2\rangle-^{85}\text{Rb}|F=2\rangle$ dual-species AI (Extended Data Fig. 1(b)). A $\pi$-blow away
pulses sequence is applied to $^{87}\text{Rb}$ atoms and a $\pi$-blow away-$\pi_c$-Repumping pulses
sequence is applied to $^{85}\text{Rb}$ atoms for states preparation and velocity-selection, after that
atoms in states $^{87}\text{Rb}|F=1\rangle$ and $^{85}\text{Rb}|F=3\rangle$. Here $\pi_c$-pulse is a co-propagating Raman pulse,
is used to transfer $^{85}\text{Rb}|F=2\rangle$ atoms to state $^{85}\text{Rb}|F=3\rangle$, the purpose of other laser pulses
are the same as those described in Extended Data Fig. 1(a). A $\pi/2$-blow away-$\pi$-blow
away-π/2 pulses sequence is applied to realize $^{85}$Rb|F=2⟩ AI and a π/2-repumping-π-repumping-π/2 pulses sequence is applied to realize $^{87}$Rb|F=2⟩ AI. Here, the repumping pulse is used to pumping atoms in states $^{87}$Rb|F=1⟩ to $^{87}$Rb|F=2⟩, the blow away-repumping pulses sequence clear the atoms residing in states $^{87}$Rb|F=2⟩ and pumping atoms in states $^{87}$Rb|F=1⟩ to $^{87}$Rb|F=2⟩ for detection.

Since a co-propagating Raman pulse is used for state inversion of $^{85}$Rb, $\omega_3$ needs to be reduced by 30 kHz after this pulse to compensate for the frequency shift caused by photon recoil.

(c) $^{87}$Rb|F=1⟩-$^{85}$Rb|F=3⟩ dual-species AI (Extended Data Fig. 1(c)). A π-blow away-π-Repumping pulses sequence is applied to $^{87}$Rb atoms and a π-blow away-π-repumping-π-blow away pulses sequence is applied to $^{85}$Rb atoms for states preparation and velocity-selection. The purpose of laser pulses are the same as those described in Extended Data Fig. 1(a) and (b). A π/2-blow away-π-blow away-π/2 pulses sequence is applied to realize $^{87}$Rb|F=1⟩ AI, and a π/2-repumping-π-repumping-π/2 pulses sequence is applied to realize $^{85}$Rb|F=3⟩ AI. The blow away-repumping pulses sequence clear the atoms residing in states $^{85}$Rb|F=3⟩ and pumping atoms in states $^{85}$Rb|F=2⟩ to $^{85}$Rb|F=3⟩ for detection.

Since a co-propagating Raman pulse is used for state inversion of $^{85}$Rb, $\omega_3$ needs to be increased by 30 kHz after this pulse to compensate for the frequency shift caused by photon recoil.

(d) $^{87}$Rb|F=2⟩-$^{85}$Rb|F=3⟩ dual-species AI (Extended Data Fig. 1(d)). A π-blow away pulses sequence is applied to $^{87}$Rb atoms and $^{85}$Rb atoms for states preparation and velocity-selection. The purpose of laser pulses are the same as those described in Extended Data Fig. 1(a) and (b). A π/2-repumping-π-repumping-π/2 pulses sequence is applied to
realize $^{87}\text{Rb}|F=2\rangle-^{85}\text{Rb}|F=3\rangle$ dual-species AI. The blow away-repumping pulses sequence clear the atoms residing in states $^{87}\text{Rb}|F=2\rangle$ and $^{85}\text{Rb}|F=3\rangle$, and pumping atoms in states $^{87}\text{Rb}|F=1\rangle$, $^{85}\text{Rb}|F=2\rangle$ to $^{87}\text{Rb}|F=2\rangle$, $^{85}\text{Rb}|F=3\rangle$ for detection.

**Improvement of the signal to noise ratio.** To improve the signal-to-noise ratio of the atom fountain, we upgraded our original experimental setup$^{31}$. We changed the 3D-MOT configuration from (0,1,1) to (0,0,1). A two-stage 2D-MOT was added to the 3D-MOT via a vacuum differential chamber. We also optimized laser wave-front and improved laser stability$^{32}$. Allan deviations of $\eta$ measurements using $^{87}\text{Rb}|F=1\rangle-^{85}\text{Rb}|F=2\rangle$ dual-species AI are shown in Extended Data Fig. 2, where (a) and (b) are the data for free evolution time $T = 70.96$ ms and $T=152.21$ ms before the setup upgrade. (c) is the data for $T=203.12$ ms after improvement of atom numbers and stability. (d) is the data for $T=203.44$ ms with rotation compensation, and (e) is the data for $T=203.164$ ms with all combined efforts.

**Assessment of systematic errors.** Systematic errors are calibrated by modulation experiments and theoretical calculation. These measures are described below.

(a) Correction of the wave vector. The phase shift difference between $^{85}\text{Rb}$ and $^{87}\text{Rb}$ atom interferometer is described as Eq. (s6). The values of $\Delta k_{\text{eff}}$ with different atom pairs are listed in Extended Data Table 1, where $T=203.164$ ms, $\tau=31$ $\mu$s, and the uncertainty of wave vector correction is $5 \times 10^{-11}$. The difference of $\Delta f_{\text{rec}}$ value is caused by the frequency change of $\omega_3$ after applying co-propagating state selection pulses.

| Test pairs       | (1) | (2) | (3) | (4) |
|------------------|-----|-----|-----|-----|
| $\Delta f_{\text{rec}}$ (kHz) | 0   | +30 | -30 | 0   |
| $\Delta k_{\text{eff}}$ (m$^{-1}$) | 159.2402 | 159.2415 | 159.2390 | 159.2402 |
| $\Delta \eta$ ($10^{-10}$) | 49435.6 | 49436.0 | 49435.2 | 49435.6 |

(1) $^{87}\text{Rb}|F=1\rangle-^{85}\text{Rb}|F=2\rangle$
(b) ac Stark shift. The ac Stark shift is caused by Raman lasers, blow away and repumping lasers. In our previous experiment\(^7\), the MIR of the Raman lasers was set to \(I_1: I_2: I_3: I_4 = 1.0: 1.0: 3.1: 14\) with an accuracy of 10\%, which was limited by the fluctuation of the Raman laser intensities. The maximum residual ac Stark shift was calibrated to be 6 kHz by modulating the Raman laser intensity from 10\% to 100\%. To reduce the shift, the MIR of the four Raman lasers is controlled to \(I_1: I_2: I_3: I_4 = 1.00: 1.00: 3.05: 14.3\). The long-term drift of the laser intensity is decreased to less than 2 \% by controlling the temperature of optics table, feedbacking, and isolation of the vibration of optics. The shift is reduced to less than 500 Hz. The dependence of the ac Stark shift on the ratio precision is shown in Extra Data Fig. 3. To estimate the influence of the ac Stark shift on \(\eta\), we simulate the shift caused by Raman lasers as

\[ \Delta \phi = 8 \tau (\phi_{\text{down}}^{\text{ac}} - \phi_{\text{up}}^{\text{ac}}), \] (s7)

where \(\phi_{\text{down}}^{\text{ac}}\) and \(\phi_{\text{up}}^{\text{ac}}\) are ac Stark shifts of the downward part and the upward part of the interference loop at the time of the second Raman pulse. This shift is mainly caused by the residual ac Stark shift associated with the Raman laser intensity gradient. Considering laser beams with a diameter of 30 mm, pulse duration \(\tau = 30 \mu s\), evolution time \(T = 203\) ms, and a residual ac Stark shift is less than 500 Hz, the calculated uncertainty of \(\eta\) caused by ac Stark shift is less than \(0.1 \times 10^{-10}\).

To investigate the ac Stark shift of blow away and Repumping lasers, we modulate the duration of blow away pulses, and measure the \(\Delta \eta_1\). The ac Stark shift contribution due to blow away lasers is evaluated as \(0.1 \times 10^{-10}\) with the uncertainty of \(0.2 \times 10^{-10}\) (Extended Data Fig. 4). According to Extended Data Fig. 1(b), (c), and (d), the blow away
and repumping lasers are different for specific combination pairs, the corresponding $\Delta \eta$ values are $\Delta \eta_2 = (0.4 \pm 0.8) \times 10^{-10}$, $\Delta \eta_3 = (0.0 \pm 0.2) \times 10^{-10}$, $\Delta \eta_4 = (-0.1 \pm 0.2) \times 10^{-10}$.

(c) Coriolis effect. Due to the horizontal velocity distribution of atom clouds, the Coriolis effect caused by the Earth rotation couples to the free-falling atoms, so that the fluctuation of position and velocity of atom clouds leads to uncertainty of $\eta$ measurement. The Coriolis effect is expressed as

$$\Delta \phi = 2 \Omega_E \cdot (\Delta v_0 \times \kappa_{\text{eff}}) \cdot T^2, \quad (s8)$$

where $\Omega_E$ is the Earth rotation, $\Delta v_0$ is the velocity difference between two species atom clouds. Since the detectors are fixed, the phase difference mainly depends on the overlap degree of the atom clouds. In our experiments, the Coriolis effect is reduced mainly by two ways, one is to overlap the atom clouds and to reduce atom temperature; the other is to compensate the rotation of the Raman lasers mirror\,\footnote{33,34}. We design and implement\,\footnote{26} a two-dimensional rotation compensation system for Raman lasers mirror. We perform rotation compensation for the east-west and the north-south direction. The phase responses to the rotation compensation are $\Delta \eta_{E-W} = 1.1 \times 10^{-9}/\Omega_E$ and $\Delta \eta_{S-N} = 1.6 \times 10^{-9}/\Omega_E$, the total residual contribution of the Coriolis effect is $\Delta \eta = (-0.1 \pm 0.4) \times 10^{-10}$.

(d) Gravity gradient. The phase shift caused by the position difference between the two atom clouds is $\Delta \phi = k_{\text{eff}} \Delta g T^2$, where $\Delta g = T_{zz} \Delta h$, and $T_{zz}$ is the gravity gradient in z-direction. The center positions of two atom clouds are measured by the time of flight (TOF) signal. The trajectory overlap of atom clouds is optimized by adjusting background magnetic field, detuning of moving molasses lasers, and velocity selection. We use three sets of pulses for gravity gradient modulation experiments. The first set of pulses is for velocity selection of $^{85}\text{Rb}$ and $^{87}\text{Rb}$ atom clouds. The second set of pulses makes $^{85}\text{Rb}$ and
$^{87}$Rb clouds to obtain recoil velocities in opposite directions, so that their velocity difference is $\Delta \nu = 24$ mm/s. The third group of pulses reverses their velocity directions. Thus, we modulate the relative position of two species atom clouds and measure gravity gradient. The uncertainty of position difference measured in our experiments is 0.79 mm which is mainly caused by time fluctuation of TOF signal. The corresponding gravity difference is $3.6 \times 10^{-10}$ g/mm, which is slightly larger than the typical value ($3.1 \times 10^{-10}$ g/mm) on the surface of the Earth. The dependence of $\eta$ measurements on the position difference of two atom clouds is shown in Extended Data Fig. 5. The uncertainty of $\eta$ measurement corresponding to gravity gradient is $2.8 \times 10^{-10}$.

The phase shift caused by the velocity difference between the two atoms clouds is $\Delta \phi = k_{eff} T_{zz} \Delta \nu \tau^3$. In our experiment, the velocity uncertainty due to the residual ac Stark shift (<125 Hz), the quadratic Zeeman shift (<100 Hz), and the Raman laser frequency difference (<100 Hz) is less than 100 µm/s. Considering $T_{zz} = 3.1 \times 10^{-7}$ g/m and $T = 203.164$ ms, the corresponding phase shift is $6 \times 10^{-12}$, which is much smaller than the error of the gravity gradient term.

(e) Quadratic Zeeman shift. In $^{87}$Rb-$^{85}$Rb 4WDR dual-species AI, the phase shift due to the quadratic Zeeman effect is given by

$$\Delta \phi = 2\pi \left( Z_{87-F} - Z_{85-F} \right) \int \left[ B^{aw}(t)^2 - B^{dw}(t)^2 \right] dt,$$

where $I_c$ is the current of the C field coil, $Z_{87-F}$ and $Z_{85-F}$ are quadratic Zeeman shift coefficients of $^{87}$Rb and $^{85}$Rb $|F, m_F=0\rangle$ states, $B^{aw}$ and $B^{dw}$ are magnetic fields of the downward and upward path, respectively. The quadratic Zeeman shift of $^{85}$Rb atoms was measured by Li et al. The Zeeman frequency shift coefficients of the magnetic sublevel of ground fine structure of $^{87}$Rb are $Z_{87-1} = -288$ Hz/G$^2$ (for $^{87}$Rb$|F=1, m_F=0\rangle$) and $Z_{87-2} = 288$ Hz/G$^2$ (for $^{87}$Rb$|F=2, m_F=0\rangle$), those of $^{87}$Rb are $Z_{85-2} = -647$ Hz/G$^2$ (for $^{85}$Rb$|F=2, m_F=0\rangle$) and $Z_{85-3} = 647$ Hz/G$^2$ (for $^{85}$Rb$|F=3, m_F=0\rangle$). The experimentally measured $\Delta \eta$
values for $^{87}\text{Rb}|F=1\rangle-^{85}\text{Rb}|F=2\rangle$ with $I_c=50$ mA, 150 mA, 200 mA, and 300 mA are shown in Extra data Fig. 6. The corresponding value of $\Delta \eta$ is fitted by

$$\Delta \eta_i = aI_c^2 + bI_c + c,$$  \hspace{1cm} (s10)

where,

$$\kappa_i = \frac{2k_{\text{eff}} g T^2}{2\pi (Z_{87,F} - Z_{85,F})}.$$  \hspace{1cm} (s11)

for $\kappa_1(Z_{87,1}, Z_{85,2})$, we get $\Delta \eta_1 = (0.5 \pm 0.3) \times 10^{-10}$ when the $I_C$ is extrapolated to 320 mA, where, the bias value ($1.4 \times 10^{-10}$) of quadratic polynomial fitting includes the contributions of zero C-field and other experimental parameters. Since the contribution of the zero C-field ($2 \times 10^{-13}$) can be ignored, the bias term is deduced from the contribution of quadratic Zeeman shift. According to Eq.(s10) and (s11), the corresponding $\Delta \eta$ values of the other three combination pairs given by using $\kappa_2(Z_{87,2}, Z_{85,2})$, $\kappa_3(Z_{87,1}, Z_{85,3})$, and $\kappa_4(Z_{87,2}, Z_{85,3})$ are evaluated as $\Delta \eta_2 = (1.3 \pm 0.8) \times 10^{-10}$, $\Delta \eta_3 = (-1.3 \pm 0.8) \times 10^{-10}$, and $\Delta \eta_4 = (-0.5 \pm 0.3) \times 10^{-10}$ respectively.

(f) Wave-front-aberration. We use the expansion-rate-selection method\textsuperscript{37} to suppress the phase noise caused by the wave-front distortion of the Raman lasers. The corresponding error due to wave-front-aberration is analyzed and estimated by modulation experiments. We use the initial temperature of 3 $\mu$K, detection beam diameters of 5 mm, 10 mm, 15 mm and 20 mm to measure the wave-front distortion. The experimentally measured $\Delta \eta$ value for $^{87}\text{Rb}|F=1\rangle-^{85}\text{Rb}|F=2\rangle$ versus the size of detection beams is shown in Extended Data Fig. 7. The actual beam diameter is 15 mm, so the contribution of wave-front distortion is fitted as $(0.5 \pm 0.5) \times 10^{-10}$.

(g) Other systematic errors. The errors caused by tides, absolute wavelength of lasers, chirp rate, mirror angle (pointing direction of the Raman beam), timing control accuracy
are suppressed in 4DWR-e AI and are small enough. The collision shift, which depends on
the density of the atoms, is also very small under present condition. The total uncertainty
of the contribution of these parameters is $1.0 \times 10^{-10}$.

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    and suppression of wave-front-aberration phase noise in weak-equivalence-principle
    tests using dual-species atom interferometers. *Phys. Rev. A* **96**, 023618(2017).
Extended Data Fig. 1 | Schematic diagram of mass and internal energy specified 4WDR dual-species AIs. (a) $^{87}\text{Rb}\left| F=1 \right., ^{85}\text{Rb}\left| F=2 \right.\right)$ dual-species AI. (b) $^{87}\text{Rb}\left| F=2 \right., ^{85}\text{Rb}\left| F=2 \right.\right)$ dual-species AI. (c) $^{87}\text{Rb}\left| F=1 \right., ^{85}\text{Rb}\left| F=3 \right.\right)$ dual-species AI. (d) $^{87}\text{Rb}\left| F=2 \right., ^{85}\text{Rb}\left| F=3 \right.\right)$ dual-species AI.
Extended Data Fig. 2 | Allan deviations of \( \eta \) measurements using \(^{85}\text{Rb}\mid F=2\)-\(^{87}\text{Rb}\mid F=1\) dual-species AI. (a) The statistical uncertainty of \( \eta \) is \( 8.0 \times 10^{-9} \) at integral time of 3200 s and the free evolution time \( T = 70.96 \text{ ms} \). (b) The statistical uncertainty is improved to \( 3.0 \times 10^{-9} \) with \( T = 152.21 \text{ ms} \). (c) The statistical uncertainty is improved to \( 5.1 \times 10^{-10} \) by the improvement of atom numbers, stability and \( T = 203.12 \text{ ms} \). (d) The statistical uncertainty is improved to \( 2.4 \times 10^{-10} \) by rotation compensation and \( T = 203.44 \text{ ms} \). (e) The statistical uncertainty is improved to less than \( 5.8 \times 10^{-11} \) by combined effort and \( T = 203.164 \text{ ms} \).
Extended Data Fig. 3 | Dependence of the ac Stark shift on the magic intensity ratio of the Raman lasers. MIR=I₁: I₂: I₃: I₄, which is magic intensity ratio of four Raman beams with frequencies of \( \omega_1 \), \( \omega_2 \), \( \omega_3 \), and \( \omega_4 \). The red dots are data before improvement when changing the Raman laser intensity from 10% to 100%, the maximum residual frequency shift is 6 kHz. The blue squares are data after improvement, and the frequency shift is less than 500 Hz. The error bars are obtained using Gaussian fitting.
Extended Data Fig. 4 | Dependence of $\eta_1$ measurements on the duration of blow away pulse. (a) The blue squares are experimental data, and the red curve is the quadratic polynomial fitting. The error bars are got by the Allan deviation with an integration time of 4480 s or 8960 s. The corresponding value of $\Delta \eta_1$ is fitted as $0.1 \times 10^{-10}$ at pulse duration of 2 ms. (b) The residuals of quadratic polynomial fit, the uncertainty of $\Delta \eta_1$ is obtained as $0.2 \times 10^{-10}$ by the deviation of residuals.
**Extended Data Fig. 5 | Dependence of η₄ measurements on the position difference of two atom clouds.** The velocity difference is 24 mm/s and the interval between velocity-selection pulses for $^{85}\text{Rb}$ and $^{87}\text{Rb}$ is 140 ms. The position difference is 3.36 mm, and the fitting value is $3.6 \times 10^{-10}$ / mm. The error bars are got by the Allan deviation with an integration time of 4480 s or 8960 s.
Extended Data Fig. 6 | Dependence of uncertainty of $\eta_1$ measurements on the C-field current. (a) The blue squares are measurements using $I_C =$ 50 mA, 150 mA, 200 mA, 300 mA. The error bars are got by the Allan deviation with an integration time of 4480 s or 8960 s. The black line is fitting curve. The corresponding value of $\Delta \eta_1$ is fitted as $0.5 \times 10^{-10}$ when $I_C$ is extrapolated to 320 mA. (b) The residuals of quadratic polynomial fit, the uncertainty of $\Delta \eta_1$ is obtained as $0.3 \times 10^{-10}$ by the deviation of residuals.
Extended Data Fig. 7 | Dependence of $\eta$ measurements on the size of detection beams. (a) The squares are measurements using detection beam with diameter of 5 mm, 10 mm, 15 mm, and 20 mm. The uncertainties of four measurements are all within $1.0 \times 10^{-10}$. The error bars are got by the Allan deviation with an integration time of 4480 s or 8960 s. The corresponding value of $\Delta \eta$ is fitted as $0.5 \times 10^{-10}$ at beams diameter of 15 mm. (b) The residuals of quadratic polynomial fit, the uncertainty of $\Delta \eta$ is obtained as $0.5 \times 10^{-10}$ by the deviation of residuals.
Schematic diagram of 4WDR-e 87Rb-85Rb dual-species AI. (a) Relevant sub-levels covering energy interval from micro-eV to giga-eV. Raman lasers with frequencies of $\omega_1$, $\omega_2$, and $\omega_3$ are used for 85Rb atoms, while that with frequencies $\omega_1$, $\omega_2$, and $\omega_4$ are for 87Rb atoms; $\omega_1$ is the detuning of $\omega_1$, $\delta_2$ is the detuning of $\omega_2$. $\omega_1$ and $\omega_2$ are detuned to the blue side of transitions 85Rb|F = 3$ to $|F' = 4$ with a detuning of $\Delta_1$ and 87Rb|F = 2$ to $|F' = 3$ with a detuning of $\Delta_2$. (b) The 4WDR-e configuration for 87Rb-85Rb dual-species AI. The blue dash lines represent LGS atoms, and red solid lines represent UGS atoms. (c) Experimental setup. PM: polarization maintaining; 3D-MOT: three-dimensional magneto-optical trap.
Figure 2

Experimental data. (a) Experimentally measured $\eta$ values, where the error corresponding to the effective wave vector is corrected. (a1), (a2), (a3) and (a4) are measurements for $\eta_1$, $\eta_2$, $\eta_2$ and $\eta_4$, respectively. (b) Allan deviation of $\eta_1$ (red squares), $\eta_2$ (black dots), $\eta_3$ (green boxes) and $\eta_4$ (blue triangles). (c) Dependence of $\eta$ values on energy, the intercept value of the fitted straight line $\eta_0 = (-0.8 \pm 1.4) \times 10^{-10}$, and the slope value $\beta = (-0.6 \pm 6.9) \times 10^5$. 