TOPICAL REVIEW — Precision measurement and cold matters

Precision measurement with atom interferometry*

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Development of atom interferometry and its application in precision measurement are reviewed in this paper. The principle, features and the implementation of atom interferometers are introduced, the recent progress of precision measurement with atom interferometry, including determination of gravitational constant and fine structure constant, measurement of gravity, gravity gradient and rotation, test of weak equivalence principle, proposal of gravitational wave detection, and measurement of quadratic Zeeman shift are reviewed in detail. Determination of gravitational redshift, new definition of kilogram, and measurement of weak force with atom interferometry are also briefly introduced.

Keywords: cold atom, atom interferometry, precision measurement

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1. Introduction

Matter waves have similar interference behavior as light waves do, atom interferometers may be achieved by coherently manipulating atomic wave packet. There are four methods to manipulate an atomic wave packet: microstructure grating,[1,2] double-slit,[3,4] stimulated Raman transition (SRT),[5] and laser standing wave grating.[6] Shimizu[4] achieved interference fringes of cold neon atoms using Young's double-slit. Laser standing wave gratings are easier to realize than artificial gratings, Bordé[7] proposed a method to experimentally display the interference characteristics of atoms via optical Ramsey oscillation. This proposal for atom interferometry (AI) experiment was realized by Riehle *et al.*[8] Laser field can be used to select internal state or external state of atoms for AI, Kasevich[5] achieved a cold atom interferometer by manipulating cold sodium atoms using two-photon SRT. The manipulating process includes several steps: preparation of atoms in initial state, splitting of atom cloud, evolution of atoms, combining of atomic wave packet, probe of internal state population, and extraction of external state information.

Due to the fast development of atom interferometers, precision measurements based on AI have also made great progress in recent years. AI can be used for measuring fundamental physics constants and parameters, such as gravitational constant,[9–11] and fine structure constant.[12–16] Atom interferometers are sensitive to the Earth's gravity field, they can be used for measuring absolute value and variation of gravitational acceleration, g; they can also be developed into atom gravimeters,[17–19] atom gravity gradiometers,[20] to satisfy the application requirements of resource exploration, geophysical studies, seismic monitoring, and experimental test of basic physics laws.[21–26] Due to Sagnac effects of interference loops, atom interferometers are inertial sensors, they can be made into high-precision atom gyroscopes,[27] and can be applied in aerospace, marine, earthquake prediction and automatic control. AI is one of the possible candidates for gravitational wave (GW) detection.[28–31] AI based Compton clock provides a new benchmark for definition of kilogram.[25] Single atom interferometer can be used to measure weak force.[32]

In this paper, we introduce the principle, features and implementation of atom interferometers, review the latest progress of determination of fundamental physics constants, measurement of gravity, test of general relativity, measurement of rotation, proposal of GW detection, and other precision measurements with AI.

2. Atom interferometry

The most common atom interferometer is SRT-based cold atom interferometer. SRT process can be illustrated by a three-level atom model. As shown in Fig. 1, single-mode laser fields ω_{13} and ω_{23} couple two ground states $|1\rangle$, $|2\rangle$ and an excited state $|3\rangle$, and cause a coherent SRT. Atomic population can be transferred among different ground states by SRT. This process is similar to the microwave Rabi oscillation between two ground states. Atoms in initial state $|1\rangle$ transit to ground state $|2\rangle$ by SRT process, and the population of state $|2\rangle$ versus Raman beam intensity presents Rabi oscillation,[33,34] which is a sine function.

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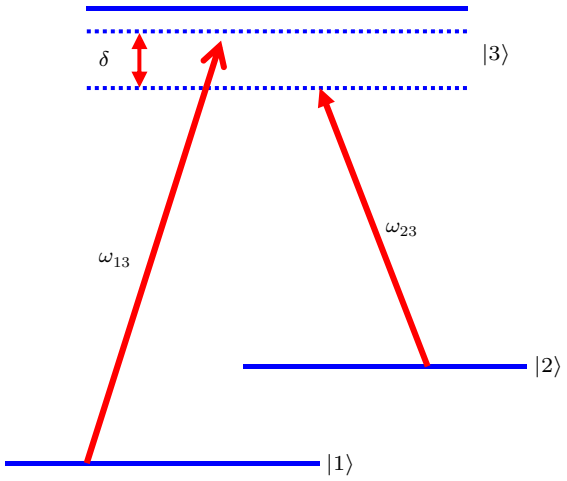


Fig. 1. Stimulated Raman transition process of three-level atomic system.

During the SRT process, the recoil momentum of atoms changes with the transference of population.[35] As shown in Fig. 2, photon momentum of counter-propagating Raman beams are $\hbar k_1$ and $\hbar k_2$, atom obtains recoil momentum, $\hbar k_1$, when it absorbs the first photon; atom obtains recoil momentum, $\hbar k_2$, when it absorbs the second photon; atom obtains recoil momentum, $\hbar k_1 + \hbar k_2$, when it emits two photons, $2\hbar k_2$.

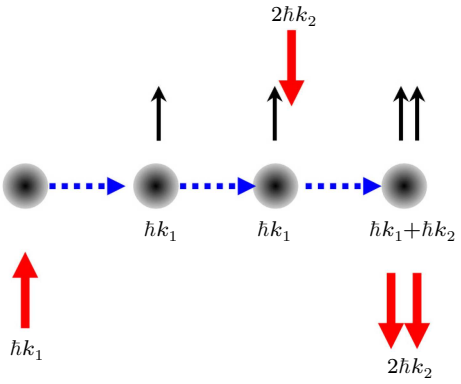


Fig. 2. Two-photon recoil momentum in stimulated Raman transition.

According to different Raman pulse sequence, cold atom interferometers can be classified as two basic types: Ramsey–Bordé (R–B) interferometer and Mach–Zender (M–Z) interferometer, other atom interferometers can be considered as the modification of these two types.

Ramsey interference spectroscopy was proposed in 1950.[36,37] Bordé proposed Ramsey spectroscopy based R–B atom interferometer in 1989,[7] and R–B atom interferometer was demonstrated using dye laser and calcium atomic beam in 1991.[8] Atom R–B interferometer can be achieved by SRT using $\pi/2$–$\pi/2$ Raman pulse sequence. A typical experimental scheme of cold atom R–B interferometer is shown in Fig. 3. Cold atoms in initial state $|1\rangle$ are split into states $|1\rangle$ and $|2\rangle$ when they interact with the first $\pi/2$-pulse, half of them stay in state $|1\rangle$, half of them transit to state $|2\rangle$, and all of the atoms freely move for a time of T, then interact with the second $\pi/2$-pulse. The dependence of population of atoms in state $|2\rangle$ (or state $|1\rangle$) on laser detuning shows R–B interference fringes.

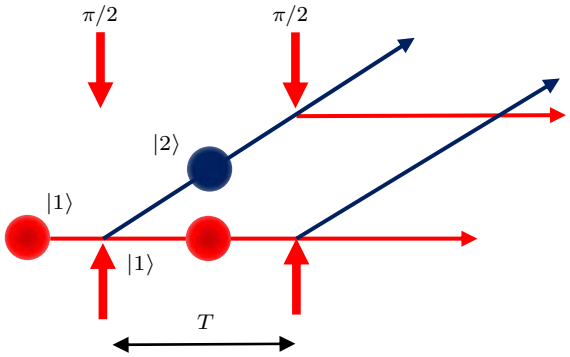


Fig. 3. Experimental scheme of Ramsey–Bordé type atom interferometer.

Take rubidium R–B interferometer for instance, cold ^{85}Rb atoms are first prepared in state $5S_{1/2}$, $F = 2$, then are operated by $\pi/2$–$\pi/2$ Raman pulse sequence. At the end of the first $\pi/2$-pulse, atoms are prepared in the coherent superposition state of two ground states $5S_{1/2}$, $F = 2$ and $5S_{1/2}$, $F = 3$. After free evolution time, T, the phase shift of the second $\pi/2$-pulse is scanned, and population of state $5S_{1/2}$, $F = 2$ or state $5S_{1/2}$, $F = 3$ are recorded to obtain R–B interference fringes.[38]

M–Z type atom interferometer[39] may be achieved by $\pi/2$–π–$\pi/2$ Raman pulse sequence. As shown in Fig. 4, atoms in initial state $|1\rangle$ interact with the first $\pi/2$-pulse, and redistributed in state $|1\rangle$ and state $|2\rangle$. Atoms in state $|2\rangle$ obtain a phase shift of laser, ϕ_1, both atoms in state $|1\rangle$ and state $|2\rangle$ form a coherent superposition state $\frac{1}{\sqrt{2}}|1\rangle + \frac{-\mathrm{i}}{\sqrt{2}}\mathrm{e}^{-\mathrm{i}\phi_1}|2\rangle$. When atoms interact with the Raman π-pulse, they undertake a π-transition, population of states $|1\rangle$ and $|2\rangle$ exchange, atoms obtain a phase shift of laser, ϕ_2, and form a coherent superposition state $-\mathrm{i}\,\mathrm{e}^{-\mathrm{i}\phi_2}(\frac{-\mathrm{i}}{\sqrt{2}}\mathrm{e}^{-\mathrm{i}\phi_1})|1\rangle - \mathrm{i}\,\mathrm{e}^{-\mathrm{i}\phi_2}(\frac{1}{\sqrt{2}})|2\rangle$. When atoms interact with the second $\pi/2$-pulse, atoms in state $|1\rangle$ redistribute in states $|1\rangle$ and $|2\rangle$ with same probability, and atoms in state $|2\rangle$ also redistribute in states $|2\rangle$ and $|1\rangle$ equally, all atoms obtain a phase shift of laser, ϕ_3. Thus, after interacting with three Raman pulses, atoms are in a coherent superposition state $-\frac{1}{2}\mathrm{e}^{-\mathrm{i}(\phi_2-\phi_1)}(1+\mathrm{e}^{\mathrm{i}(\phi_3-2\phi_2+\phi_1)})|1\rangle - \frac{\mathrm{i}}{2}\mathrm{e}^{-\mathrm{i}\phi_2}(1-\mathrm{e}^{-\mathrm{i}(\phi_3-2\phi_2+\phi_1)})|2\rangle$. Population of state $|1\rangle$ or state $|2\rangle$ depends on the phase shifts of Raman pulses (ϕ_1, ϕ_2, ϕ_3), M–Z type interference fringes can be observed by scanning the phase shifts of Raman pulses, and the phase shifts of Raman pulses can be controlled by an electro-optical modulator or an acousto-optic modulator. The distribution of magnetic field may affects the stimulated Raman process,[40] it is necessary to determine the direction of quantization axis in interference area. A typical M–Z type interference fringe is shown in Fig. 5,[39] the half-wave voltage of the electro-optical modulator is 125 V, and the contrast of fringes is $\rho = 0.37$.

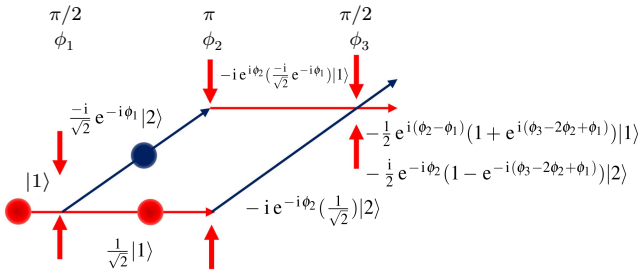


Fig. 4. Experimental scheme of Mach–Zender type atom interferometer.

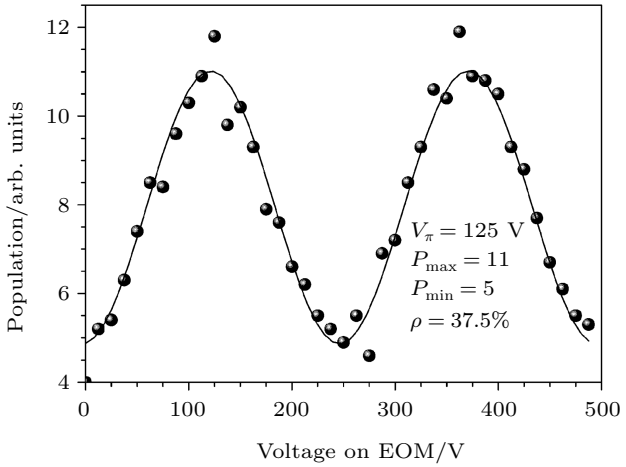


Fig. 5. Mach–Zender type interference fringe. The relative population depend on the voltage applied to the electro-optical modulator.[39]

3. Determination of fundamental physics constants

Determination of fundamental physics constants are important for basic theory, precision measurements, new definition of time units, further improvement of the accuracy of satellite positioning, etc. Fast development of AI in recent years, provides great convenience for measuring gravitational constant and fine structure constant, new progress in this area is of great inspiration.

The traditional tools to measure gravitational constant, G, are the torsion balances and precision balances,[41] both of them adopt macroscopic objects as testing quality. In 2003, Tino's group carried out the first measurement of G using AI.[42] The process of experimental measurement of G using an atom interferometer is summarized as follows. Two cold atom clouds, which are prepared in a same magneto-optical trap (MOT), are launched up vertically at different velocity in succession. Due to the gravity, the first atom cloud may fall with the same velocity as the second one, which was launched up at lower velocity. By this method, one can produce two atom clouds with similar parameters in top and bottom parts of an MOT chamber. Raman pulses for splitting, reflecting and combing atoms can be applied to two atom clouds simultaneously. The value of gravity gradient can be obtained by directly subtracting the phase shifts of two atom interferometers. Some well machined tungsten blocks are placed evenly around the device to modify gravity field near two atom clouds. G can be accurately measured by moving these tungsten blocks. Tino's group obtained the primary data of G using the above experimental methods in 2006 with a relative uncertainty of 0.01.[9] Kasevich's group reported a new result of G measured by AI in 2007,[10] they used two atom interferometers to measure the gravity gradient,[20] two atom interferometers are vertically separated. A lead block, which can be moved vertically, is used to change gravity field around these two interferometers. The relative uncertainty of measured value of G is 4.0×10^{-3}. Tino's group improved experimental measurement of G in 2008, the relative statistic uncertainty is 1.6×10^{-3}, and the relative systematic uncertainty is 4.5×10^{-4},[43] they modified the atom preparation system, measurement system and Raman beam in 2010,[44] improved the signal to noise ration and long-term stability. The relative uncertainty of measurement realized in 2014 is 1.5×10^{-4}.[11]

Fine structure constant, α, is usually measured by fine structure splitting of atoms,[45] quantum Hall effect,[46] and electron anomalous magnetic moment.[47] The recommended value of α in CODATA-2010 is 1/137.035999074, and the relative uncertainty of this value is 3.2×10^{-10}.[48] In recent years, a new method for determination of α based on AI is developed, one can indirectly measure the ratio of Planck constant and atomic mass, h/m, using AI, and then extract the value of α by h/m. The calculation formula for α can be expressed with h/m as

$$\alpha^2 = \frac{2R_\infty}{c}\frac{m_\mathrm{p}}{m_\mathrm{e}}\frac{m}{m_\mathrm{p}}\frac{h}{m}, \tag{1}$$

where c is the speed of light in vacuum, m_p is the mass of proton, and m_e is the mass of electron. As long as the value of h/m is measured, the value of α can be obtained. Interference process of atoms depends on the momentum exchange between light and atoms, the recoil velocity of atoms, υ_r, during interference process can be measured by AI. Recoil velocity is proportional to h/m, that is $\upsilon_\mathrm{r} = (h/m)(k/2\pi)$. Thus h/m can be determined by υ_r using AI.

In 1994, Chu's group measured the ratio of Planck constant and mass of cesium atoms, h/m_{Cs}, using a cesium atom interferometer, they thus obtained the value of α. The measurement uncertainty is 1×10^{-7},[12] which is the first measurement of α using AI. They improved their experiment and measured the value of α with relative uncertainty of 7.4×10^{-9}[13] in 2002. Clade *et al.* measured fine structure constant using a rubidium atom interferometer with a relative uncertainty of 6.7×10^{-9} in 2006.[14] Cadoret *et al.* improved the accuracy of the measurement of α to 4.6×10^{-9} in 2008.[15] Bouchendira *et al.*[16] measured α using an atom interferometer with an uncertainty of 6.6×10^{-10} in 2011.

4. Measurement of gravity

Atom interferometers are new type gravity measuring instruments. The information of gravity field, which influence on atom interference process, can be extracted by phase shift of the interference fringes. The principle of atom gravimeters can be simply described as Fig. 6, if atom clouds do not suffer any external gravity ($g = 0$), the interference loop will be a parallelogram as solid line in Fig. 6, there is no path difference between two atom clouds, the phase shift of interference fringes is zero. While, if the gravity field is considered ($g \neq 0$), the interference paths of atom clouds will follow the parabolic trajectory (dash line in Fig. 6). The final phase shift of interference fringes in gravity field, $\Delta\phi$, can be described as

$$\Delta\phi = k_{\text{eff}} g T^2, \tag{2}$$

where k_{eff} is the effective wave vector of Raman beams, and T is the time interval between Raman pulses. According to Eq. (2), the phase shifts of atom interference fringes depend on g, k_{eff}, and T. While k_{eff} and T can be accurately controlled by the time-frequency technology. When the phase shift, $\Delta\phi$, is measured, it is possible to achieve precision measurement of the absolute value of g.

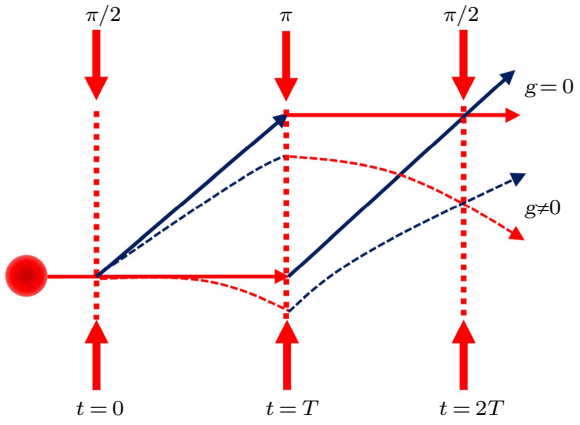


Fig. 6. Schematic diagram of atom gravimeter.

4.1. Absolute gravity measurement

Kasevich *et al.*[6] experimentally demonstrated gravity measurement using a laser-cooled sodium atom interferometer in 1991, the resolution of their measurement is $\Delta g/g = 3 \times 10^{-6}$; their improved measurement resolution in 1992 is $\Delta g/g = 3 \times 10^{-8}$.[49] Peters *et al.*[18] reported a precision measurement of g with a resolution of $\Delta g/g = 1 \times 10^{-10}$ using a cesium interferometer in 2001. Zhou *et al.*[19] demonstrated local gravity measurement and solid tide observation using a compact cold rubidium atom gravimeter in 2011. The solid tidal data of the Earth are shown in Fig. 7, the dotted line is experimental data, and the solid line is calculation curve according to the theoretical model. If the chirp rate equals the Doppler shift due to the gravity, the gravitational phase shift of interference fringes exactly compensates the phase shift of Raman beams. The short-term sensitivity of the atom gravimeter evaluated using Allan variance[50] is 2.0×10^{-7} g/$\sqrt{\text{Hz}}$, and the measurement resolution under 1888 s' integration is $\Delta g/g = 4.5 \times 10^{-9}$.

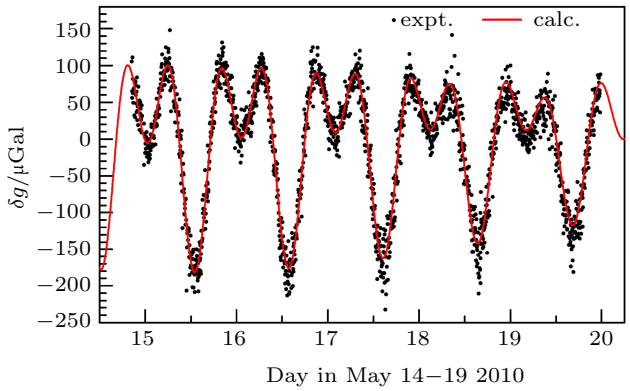


Fig. 7. Gravity data measured at Wuhan during May 14–19, 2010.[19]

Ultracold degenerate gases are good candidates for atom gravimeters due to their obvious wave characteristic. Roati *et al.*[51] used degenerate Fermi gases in gravity measurement in 2004; Debs *et al.*[52] measured gravity using interference information of rubidium Bose–Einstein condensate (BEC) in 2011. However, compared with fountain type cold atom gravimeters, the equipment and the experimental process of gravimeters using degenerate Fermi gases or BECs are too complicated to actual application.

Usually, Raman pulse sequence, $\pi/2$–π–$\pi/2$, are used to manipulate atoms to form an interference loop in a fountain type cold atom gravimeter. In this case, atoms in different paths are in different internal states, frequency shifts due to the fluctuation of magnetic field and light field are important sources of noise and syetematic errors. To solve these problems, Malossi *et al.*[53] demonstrated an AI scheme based on double-Raman transition in 2010. Fray *et al.*[21] manipulated atoms to interfere using Bragg diffraction in 2004, and obtained atom interference fringes by detecting external states of atoms. Altin *et al.*[54] demonstrated an atom gravimeter based on Bragg diffraction in 2013, and the measurement resolution is $\Delta g/g = 2.7 \times 10^{-9}$.

It is interesting to compare the capabilities of atom gravimeters with classical ones. Merlet *et al.*[55] comparatively investigated the capabilities of an atom gravimeter and a traditional absolute gravimeter in 2010, the measurement accuracies of two types of gravimeters coincide with each other at the level of (4.3 ± 6.4) μGal (1 μGal $\simeq 10^{-9}$ g). Poli *et al.*[56] carried out a similar experiment using a cold atom gravimeter and a traditional gravimeter in 2011. Although the capability of atom gravimeters is on a par with a classical gravimeters at present time, there is great potential to

improve the accuracy, the sensitivity and the resolution of an atom gravimeter by technical innovation. Kasevich's group improved the resolution of an atom gravimeter by extending the interval time in 2013,[57] they achieved a resolution of $\Delta g/g = 6.7 \times 10^{-12}$ under the condition of $T = 1.15$ s; Hu *et al.*[58] improved the short-term sensitivity of an atom gravimeter to 4.2×10^{-9} g/$\sqrt{\text{Hz}}$ by adding active vibration isolation system to the retro-reflecting mirror of Raman beams. Tino's group improved the sensitivity of an atom gravimeter by decreasing the long-term drift of the system in 2014,[59] their short-term sensitivity is 3×10^{-9} g/$\sqrt{\text{Hz}}$, and the resolution at integration time of 8000 s is $\Delta g/g = 5 \times 10^{-11}$.

An atom gravimeter has a higher sensitivity, but its system structure is too complex, and its technology is too sophisticated. The key problem of actual application of atom gravimeters is how to make the system miniature and robust. In 2008, Le Gouët *et al.*[60] improved the sample rate by shorting the interval time of Raman pulses, realized a compact atom gravimeter with a short-term resolution of $\Delta g/g = 1.4 \times 10^{-8}$. Landragin's group[61,62] demonstrated a one-laser-beam cold atom gravimeter in 2010, the short-term resolution is $\Delta g/g = 1.7 \times 10^{-7}$ at integration time of 1 s. Butts *et al.*[63] demonstrated an atom gravimeter with millisecond interrogation times in 2011. McGuinness *et al.*[64] demonstrated a high data-rate atom gravimeter which is optimized to operate at rates up to 330 Hz with a sensitivity of 3.7×10^{-5} g/$\sqrt{\text{Hz}}$. In 2013, Bidel *et al.*[65] demonstrated a cold atom gravimeter dedicated to field application, its sensitivity is 42 μGal/$\sqrt{\text{Hz}}$ ($\simeq 4.2 \times 10^{-8}$ g$\sqrt{\text{Hz}}$), and its accuracy is 25 μGal (2.5×10^{-8} g); Andia *et al.*[66] demonstrated a compact atom gravimeter using Bloch oscillation technique, and the sensitivity is $\Delta g/g = 4.8 \times 10^{-8}$ at an integration time of 4 minutes. Hauth *et al.*[67] demonstrated a compact gravimetric atom interferometer with a sensitivity of 3×10^{-8} g. Wu *et al.*[68] demonstrated an atom gravimeter for field applications with a sensitivity of 1.0×10^{-7} g/$\sqrt{\text{Hz}}$.

4.2. Gravity gradient measurement

Gravity gradient can be determined by differentially measuring the gravities of two different sites. The accuracy of gravity gradient measurement depends on the capability of a gravity gradiometer. In absolute gravity measurements, vibrational noise is the main source which limits the sensitivity and the accuracy of a gravimeter. While in gravity gradient measurements, sensitivity can be greatly improved by reducing vibrational noise using common-mode rejection technology.

Kasevich's group[20] achieved common-mode differential measurement of absolute gravity using two vertical stacked atom gravimeters in 1998, and demonstrated the first measurement of gravity gradient tensor using AI; they optimized the experimental parameters in 2002, and achieved differential measurement of gravity with a sensitivity of 4×10^{-9} g/$\sqrt{\text{Hz}}$,[69] the resolution of gravity differential measurement is $\Delta g/g = 1 \times 10^{-9}$, and the corresponding sensitivity of gravity gradient is 4 E/$\sqrt{\text{Hz}}$ (1 E = 10^{-9} s^{-2}). Yu *et al.*[70] began to develop an atom gravity gradiometer for space experiments in 2006. Tino's group[9] established an atom gravity gradiometer for determining G, which is different from the double-gravimeter configuration of Kasevich's group, they achieved a differential gravity measurement with a resolution of $\Delta g/g = 2 \times 10^{-8}$;[43,44] they demonstrated a short-term sensitivity of 9×10^{-9} g/$\sqrt{\text{Hz}}$[71] in 2012 and further improved the short-term sensitivity to 3×10^{-9} g/$\sqrt{\text{Hz}}$,[59] the resolution of gravity differential measurements after 8000 s integration is $\Delta g/g = 5 \times 10^{-11}$. In 2013, Bidel *et al.*[65] measured the gravity gradient in the vertical direction by placing a miniaturized atom gravimeter in an elevator, the resolution of gravity gradient is 4 E. In 2014, Duan *et al.*[72] demonstrated an atom gravity gradiometer by dual-fringe-locking method with a short-term sensitivity of 670 E/$\sqrt{\text{Hz}}$.

5. Test of equivalence principle

Equivalence principle (EP) is one of the basic assumptions of Einstein's general relativity. EP includes the universality of free fall (UFF) which known as weak equivalence principle (WEP), the local Lorentz invariance (LLI) and the local position invariance (LPI). Some theories predicted that there should be new interaction forces which depend on size, materials, speed, and position of objects. In other words, the EP will be broken in some extent, and the precision tests of EP have scientific significance.

There are plenty of EP test experiments using macroscopic objects, but no experiments were found to break the EP until now. What will happen if we use microscopic particles in EP test experiments? The motion of microscopic particles needs to be described by quantum mechanics rather than by Newtonian mechanics, so there should be some conceptual problems in free fall experiments using microscopic particles.[73] Since 1960s, free-falling microscopic particles in gravity field have been studied theoretically and experimentally.

The difference between gravitational accelerations of two objects, which is due to different materials, is a key parameter in the WEP test experiments. Assuming that $a_{1,2}$ are gravitational accelerations of two objects, m_{g} is the gravitational mass, m_{i} is the inertial mass, and the relative difference of gravitational acceleration of two objects can be described as[73]

$$\eta = \frac{(a_1 - a_2)}{(a_1 + a_2)/2} = 2\frac{(m_{\text{g}}/m_{\text{i}})_1 - (m_{\text{g}}/m_{\text{i}})_2}{(m_{\text{g}}/m_{\text{i}})_1 + (m_{\text{g}}/m_{\text{i}})_2}, \tag{3}$$

where η is called Eötvös factor. If WEP holds, then $m_{\text{g}} = m_{\text{i}}$, $\eta = 0$; otherwise, $\eta \neq 0$. Take ^{85}Rb and ^{87}Rb for instance, the

accuracy, η, of WEP test depends on the measurement accuracy of gravitational acceleration of each isotope atoms. The Eötvös factor can be expressed as

$$\eta = \frac{g_{87} - g_{85}}{(g_{87} + g_{85})/2}. \quad (4)$$

Traditional WEP tests include torsion balance experiments,[74] drop tower experiments,[75] lunar laser ranging experiments,[76] and macroscopic gyros experiments.[77–79] There are few WEP test experiments using microscopic particles, and neutrons were used to test the WEP[80,81] with a poor accuracy. Development of AI provides a new way for the WEP test using microscopic particles.[82] Compared with neutrons, cold atom interferometers can be used to test WEP with higher precision due to lower velocity and better coherence of cold atoms. Theoretical analysis showed that the precision of WEP test experiments using atom interferometers is expected to reach 10^{-15}.[83]

A group in Max–Planck Institute for Quantum Optics completed the first WEP test experiment based on atom interferometers in 2004.[21] They used moving molasses to form ^{85}Rb and ^{87}Rb fountains, and used Bragg diffraction to achieve external state interference. The test accuracy is $(1.2 \pm 1.7) \times 10^{-7}$. A group in French Aerospace Laboratory tested WEP using free-falling ^{85}Rb and ^{87}Rb atoms in 2013 with an accuracy of $(1.2 \pm 3.2) \times 10^{-7}$.[22] In 2014, Rasel's group in Leibniz University demonstrated WEP test using ^{87}Rb and ^{39}K atom interferometers with an accuracy of $(0.3 \pm 5.4) \times 10^{-7}$;[23] Tino's group demonstrated WEP test using bosonic and fermionic isotopes of strontium atoms with an accuracy of $(0.2 \pm 1.6) \times 10^{-7}$.[24] In addition, Müller is actively planning a WEP test experiment using cesium and lithium atoms, and is building a lithium atom interferometer.[84]

The sensitivity of an atom interferometer depends on the free evolution time of atoms. To increase the free evolution time, it is necessary to develop large-scale atom interferometers. Kasevich's group demonstrated a light-pulse atom interferometer with a duration of 2.3 s, and the inferred sensitivity is 6.7×10^{-12} g.[57] They further enhanced the readout of the 10-meter atom interferometer by a phase shear method.[85] Zhan's group designed and developed a 10-meter-fountain type atom interferometer[50] for the WEP test experiment, the schematic diagram of 10-meter atom interferometer is shown in Fig. 8. The maximum fountain height is 12.3 m, and the main part of the interferometer includes the bottom MOT, the vacuum tube, and the top MOT. The bottom MOT is used to prepare ^{85}Rb–^{87}Rb fountains; the top MOT is used to prepare free falling clouds of rubidium and lithium atoms; Zeeman slowers are used to supply atom source for MOTs. Based on this setup, dual-MOT of ^{85}Rb–^{87}Rb has been achieved,[86] and dual-species fountain signal and interference fringes using double-Raman transition are observed. In addition, Chen *et al.*[87] proposed a new data processing method to suppress the vibrational noise in non-isotope dual-atom-interferometer-based WEP test experiments, Tang *et al.*[88] designed and demonstrated a compact stable active low-frequency vibration isolation system for decreasing the vibrational noise in AI caused by the reflecting mirror of Raman beams.

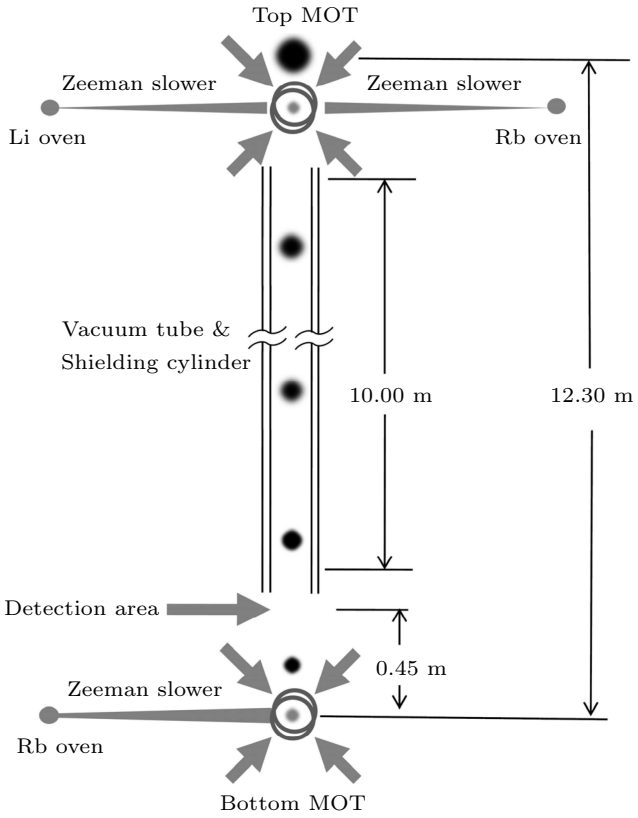


Fig. 8. Schematic diagram of 10-meter atom interferometer at Wuhan.

Another application of AI in fundamental physics is to determine gravitational redshift. Müller *et al.*[25,26] analyzed the previous experimental results of gravity measurements using atom interferometers. They considered that the gravitational redshift can be measured by atom interferometers, and the experimental data are consistent with the theoretical prediction at the level of 7×10^{-9}. This precision is four orders of magnitude better than similar experiments using atom clocks. The publication of this result caused some controversies.[89–92] In order to solve the dispute of redshift, Schleich *et al.* proposed Kasevich–Chu interferometer scheme[93] based on operator algebra. This interferometer is an accelerometer or a gravimeter.

6. Measurement of rotation

The Sagnac effect of a light interference loop is the basis of laser gyros and optical fiber gyros. Atom interference loop can also be used as gyros to measure the rotation.[27] Bordé *et al.*[8] firstly demonstrated the Sagnac effect of a calcium atomic beam R–B interferometer, which was achieved by four

standing laser fields. Due to lower velocity and longer wavelength of matter waves, AI-based gyros are more sensitive than laser gyros.[94] The principle of M–Z type atom gyros is shown in Fig. 9.

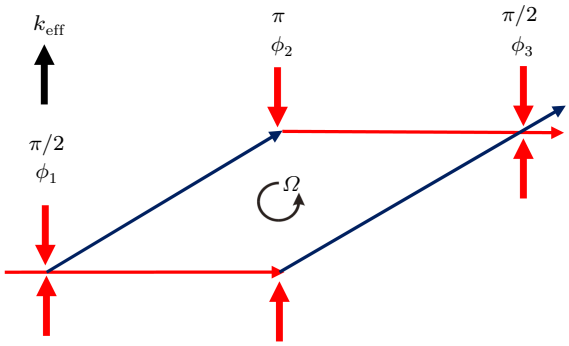


Fig. 9. Schematic diagram of an atom gyroscope.

When an atom interferometer is placed in a frame with rotation rate, Ω, the phase shift of interference loop caused by rotation is

$$\phi_\Omega = -2k_{\rm eff}(\Omega \times \upsilon)T^2, \tag{5}$$

where υ is the velocity of atoms. According to the status of atoms involved in interferometers, atom gyros can be classified into four types: thermal atomic beam gyros, cold atoms gyros, chip-based atom gyros, and quantum vortex gyros. The sensitivity of atom gyros, also known as angle random walk (ARW), depends on two parameters: atom number and scaling factor. The more atoms there are, the better the sensitivity is; the bigger the scaling factor is, the better the sensitivity is.

Thermal atomic beam gyros have better sensitivity, better long-term stability, and broad bandwidth due to more atoms and bigger scale factor. Pritchard's group[95] demonstrated the Sagnac effect of an atomic beam interferometer and measured the rotation rate of the Earth in 1997. Kasevich's group[96] realized an atomic beam gyro by SRT, with the short-term ARW being 2×10^{-8} (rad/s)/$\sqrt{\rm Hz}$. They improved the resolution of gyro to 6×10^{-10} rad/s (1 s integrated time) in 2000.[97] In 2006, they further improved the parameters of the atomic beam gyro with an ARW of 3×10^{-6} $(^\circ)/\sqrt{h}$ ($\simeq 9\times10^{-10}$ (rad/s)/$\sqrt{\rm Hz}$), a bias stability of 6.7×10^{-5} $(^\circ)/h$ ($\simeq 3.2\times10^{-10}$ rad/s) at 1.7×10^4 s.[98] These are the best parameters of an atom gyros up to now.

Although the sensitivity of a thermal atomic beam gyro is better, its volume is too large for practical applications. A feasible way to solve this problem is to shorten interference area by substituting thermal atomic beam with cold atoms. Canue *et al.*[99] designed and achieved a cold atom gyro using two counter-propagating cold-atom clouds in 2006, with the bias stability being 2.2×10^{-6} rad/s, and 10-minutes integral bias stability being 1.4×10^{-7} rad/s. Müller *et al.*[100] generated a high-flux (10^{10} atoms/s) atomic beam for cold atom gyro in 2007, and they demonstrated a compact dual-loop cold atom gyro in 2009.[101] Tackmann *et al.*[102] achieved a small cold atom gyro with self-collimation large loop area in 2012, and the ARW is 6.1×10^{-7} (rad/s)/$\sqrt{\rm Hz}$. Kasevich's group[103] designed and achieved a small cold atom gyro using $\pi/2$–π–π–$\pi/2$ Raman pulses sequence with an ARW of 8.5×10^{-8} (rad/s)/$\sqrt{\rm Hz}$, and they measured the rotation rate of the Earth with a resolution of 2×10^{-7} rad/s at $T = 1.15$ s in 2013.[57]

Ultracold atoms or BECs can be guided to achieve a spatial interference loop for rotation measurement. Shin *et al.*[104] realized an atom interferometer using BECs in a double well. Tolstikhin *et al.*[105] demonstrated the Sagnac effect of a matter wave interferometer using cigar-shaped BECs. Wu *et al.*[106] implemented an atom gyro based on mobile waveguides. They identified the rotation signal which is 10 times of the Earth's rotation rate. Baker *et al.*[107] designed a chip-based ring trap which can be used to guide cold atoms, molecules, or BECs to form gyros. Debs *et al.*[108] studied the characteristics of BECs using three different output couplers. Yan[109] proposed an idea to achieve close-loop atom interferometers on a chip using a moveable waveguide, and atoms can be split and combined by a moveable microwave waveguide.

Vortex characteristics of superfluid may also be used to measure the rotation. Stringari[110] proposed a vision of rotation measurement based on quantum vortex characteristic of BECs. Hodby[111] observed three-dimensional Sagnac effect in BECs. Avenel *et al.*[112] demonstrated a gyro based on Josephson effect of superfluid ^{3}He and ^{4}He. Narayana *et al.*[113] demonstrated the Sagnac effect of superfluids. Thanvanthri *et al.*[114] proposed a scheme of atom gyro using vortex superposition state of BECs.

7. Detection of gravitational wave

The existence of GW was predicted by Einstein in 1916, but there are only few GW observation results till now.[115–117] Research on the GW detection using matter wave interferometers started in 1979,[118] and more and more attention has been paid to this method since AI was applied in precision measurement. In 2004, Chiao *et al.*[119] studied and found that matter-wave interferometer gravitational wave observatory (MIGO) will be more sensitive than laser interferometer detectors, while Roura *et al.*[120] questioned their conclusions. In 2007, Tino and Vetrano[121] carefully analyzed the scheme of MIGO, they considered that short-baseline MIGO can detect low-frequency GW with a sensitivity comparable to large-baseline laser interferometers. Wicht *et al.*[122] proposed a solution to GW detection based on internal state interference of molecule in 2008. Dimopoulos *et al.*[28] proposed a space-based atom interferometer GW detector in 2009, and its expected strain sensitivity is $10^{-19}/\sqrt{\rm Hz}$ within 1–10 Hz band.

Lorek *et al.*[123,124] proposed a GW detection scheme using an atom interferometer based on orienting atoms in space. In 2011, Hogan *et al.*[29] proposed a low-orbit space atom interferometer GW detector, where the expected detection band is 50 mHz–10 Hz, and the sensitivity is expected to reach $10^{-18}/\sqrt{\text{Hz}}$; Hohensee *et al.*[30] considered that MIGO can detect GW within a frequency band of mHz–Hz; Yu *et al.*[125] proposed an atom interferometer detector with similar structure as laser interferometers; Bender *et al.*[126] analyzed the error sources in the GW detection using an atom interferometer; Lepoutre *et al.*[127] compared different diffraction means of atoms used in atom GW detectors. Another new proposal of the GW detector based on atomic beam interferometers was proposed by Gao *et al.*[31] in 2011, where a supersonic atomic beam is used to enhance the signal to noise ratio, and the atomic beam is split, deflected, and combined to interfere by laser standing-wave gratings instead of a physical grating. GW can be detected by phase shift information of the two atom beams, and the detectable GW frequency band is within 10–1000 Hz. Graham *et al.*[128] proposed a GW detector based on optical clocks and atom interferometers in 2013, and the detector can run in long baseline which has immunity against the laser frequency noise.

Although the optimal scheme and the practical experimental details of matter-wave interferometer GW detectors are not very clear, AI provides us a possible breakthrough in the GW detection.

8. Other precision measurements

In addition to measuring gravity and rotation, the phase of atom interference fringes is also very sensitive to external magnetic field. The quadratic Zeeman shift of certain transition of atoms can be measured precisely by an atom interferometer. The transition between insensitive magnetic sublevels is usually called "clock transition" in atom fountain clocks, precision measurement of quadratic Zeeman shift of clock transition is very important for atom frequency standards and other high-resolution spectroscopy experiments. Li *et al.*[40] measured the quadratic Zeeman shift of clock transition of ^{85}Rb using an atom interferometer in 2009. The quadratic Zeeman shift is determined by measuring the resonance frequencies of coherent population transition in Raman transition process. The frequency shifts of the transitions $5P_{1/2}$, $F = 2, m_F = -2 \rightarrow 5P_{1/2}$, $F = 3, m_F = -2$ and $5P_{1/2}$, $F = 2$, $m_F = 2 \rightarrow 5P_{1/2}$, $F = 3$, $m_F = 2$ of ^{85}Rb are measured as a function of magnetic field, and the intensity of magnetic field is proportional to the current applied to magnetic coils. The scale factor of the magnetic field is 1576.9 ± 1.3 mG/A. The dependence of transition probability of the ground-state clock transition on two-photon detuning, is determined by applying bias magnetic field along the direction of Raman beams. The coefficient of quadratic term corresponding to the quadratic Zeeman shift of clock transition is 1296.8 Hz/G^2. The error caused by scaling the magnetic field is 2.1 Hz/G^2, and the error caused by the fitting is 2.5 Hz/G^2. Wu *et al.*[129] measured the quadratic Zeeman coefficient of ^{87}Rb clock transition by using the Ramsey atom interferometer with an uncertainty of less than 1 Hz/G^2, and they experimentally verified the Breit–Rabi formula.[130] Zhou *et al.*[131] measured magnetic field gradient with an atom interferometer, the resolution of 90-s integration time is 300 pT/mm. Hu *et al.*[132] demonstrated a differential method to reject the common-mode noise and to improve the measurement resolution of magnetic field gradient by two simultaneously operated atom interferometers.

It is possible to redefine the kilogram by AI. In 2010, Müller *et al.*[25] proposed that atoms involved in atom interferometers can be considered as clocks running at Compton frequency, ω_c. ω_c is relevant to the rest mass of atoms: $\omega_c = mc^2/\hbar$, that is, the unit of quality can be defined by Compton frequency. Wolf *et al.*[89,133] doubt this scenario. They believed that, Compton phase difference between two atom interference paths is zero in the framework of general relativity and other theories. Thus, gravitational redshift cannot be tested using AI-based Compton frequency unless the Schiff conjecture and other physics laws are violated. Müller[90] responded that Wolf *et al.* misused Schiff conjecture when they reached their conclusion, and gravitational redshift effect can be directly tested by atom interferometers. In 2013, Müller *et al.*[134] experimentally demonstrated a Compton clock. They calibrated an atom interferometer using an optical frequency comb, synchronized the oscillator by pulse spectrum of recoil atoms, and directly linked the mass of the particle to the time. In short, Compton clock can be used to measure "kilogram" with "seconds".[135]

The capability of atom interferometers in measurement of gravity can be used to test Newton's inverse square law at medium or short distance.[136] Lepoutre *et al.*[137] measured the phase shift caused by atom–surface van der Waals interaction using AI. Since the collective interference effect of single atoms is equivalent to interference of atom cloud, single-atom interferometers can be used for measuring weak force. Preparation of single atoms in optical dipole trap is the precondition for achieving a single-atom interferometer. The first single-atom trap is demonstrated by Frese *et al.*[138] in 2000. Zhan's group has achieved optical bottle trap,[139] hybrid red-blue detuned optical trap,[140] and phase decoherence suppression[141] of single atoms. Parazzoli *et al.*[142] observed interference of matter waves using free falling single atoms, and demonstrated the weak force measurement by a single-atom interferometer in 2012. They directly detected the velocity distribution of free falling single atoms, and measured the temperature of single atoms using coherence length of atomic

wave packet. The single-atom interferometer can detect the force of 3.2×10^{-27} N level with spatial resolution of micrometer scale. This sensitivity can be used to measure Casimir–Polder potential.

9. Summary

Development of AI provide experimental techniques for precision measurements based on atomic and molecular physics. Traditional precision measurements, such as determination of gravitational constant, measurement of fine structure constant, test of weak equivalence principle, and detection of gravitational wave, will benefit from the AI, deepen our understanding of general relativity and the origin of the universe. Principle demonstration, technology development and practical application of atom gravimeters, atom gravity gradiometers and atom gyros, will fully exert the advantages of AI. Precision measurement with AI is a new cross field which is full of vigor and vitality, and it is worth our attention.

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