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Measurement of Local Gravity via a Cold Atom Interferometer *

ZHOU Lin(周林)[1,2,3], XIONG Zong-Yuan(熊宗元)[1,2,3], YANG Wei(杨威)[1,2,3], TANG Biao(汤彪)[1,2,3], PENG Wen-Cui(彭文翠)[1,2,3], WANG Yi-Bo(王一波)[1,2,3], XU Peng(许鹏)[1,2,3], WANG Jin(王谨)[1,2], ZHAN Ming-Sheng(詹明生)[1,2**]

[1] *State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences-Wuhan National Laboratory for Optoelectronics, Wuhan 430071*
[2] *Center for Cold Atom Physics, Chinese Academy of Sciences, Wuhan 430071*
[3] *Graduate University of the Chinese Academy of Sciences, Beijing 100049*

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We demonstrate a precision measurement of local gravity acceleration g in Wuhan by a compact cold atom interferometer. The atom interferometer is in vertical Mach–Zehnder configuration realized using a $\pi/2-\pi-\pi/2$ Raman pulse sequence. Cold atoms were prepared in a magneto-optical trap, launched upward to form an atom fountain, and then coherently manipulated to interfere by stimulated Raman transition. Population signal vs Raman laser phase was recorded as interference fringes, and the local gravity was deduced from the interference signal. We have obtained a resolution of 7×10^{-9} g after an integration time of 236 s under the best vibrational environment conditions. The absolute g value was derived from the chirp rate with a difference of 1.5×10^{-7} g compared to the gravity reference value. The tidal phenomenon was observed by continuously monitoring the local gravity over 123 h.

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Since Chu and Kasevich[1] first demonstrated light pulse atom interferometry for gravity measurement in 1991, atom interferometry has become a powerful tool for precision measurement in many fields, such as gravimeter,[2–6] gyroscope,[7,8] and gravity gradiometer.[9–11] It is also used to measure fundamental constants, such as the fine structure constant α,[12–15] Newtonian constant of gravity G,[16,17] and to test fundamental physics laws, such as weak equivalence principle,[18] isotropy of post-Newtonian gravity,[19] gravitational red shift,[20] and the inverse square law.[21] Recently, due to the rapid development of new techniques and methods of atom interferometry,[22,23] experimental schemes based on atom interferometry have been proposed to further test the weak equivalence principle[24] and neutrality,[25] to detect gravitational wave[26] and dark energy,[27] and to measure the curvature spacetime.[28]

However, to build and to run an atom interferometer is not easy due to the complexity of the interferometers themselves. A typical atom interferometer includes lasers for cooling, trapping and manipulating atoms, high frequency electro-optical modulators (EOMs) for producing Raman beams. The disadvantage of using EOM is that one cannot split the carry and sideband beams completely. To simplify the requirement, in this Letter we report a design and realization of a compact atom interferometer and its successful application in measuring the local gravity and the tidal effect. By using the ^{85}Rb atom instead of ^{87}Rb, the Raman laser frequency difference is decreased to 3.0 GHz which can be conveniently and high efficiently generated by an acousto-optical modulator (AOM).[29] Raman beams, produced by AOM instead of EOM, are separated spatially and more convenient to steer. With this compact atom interferometer, we performed a precision measurement of local gravity.

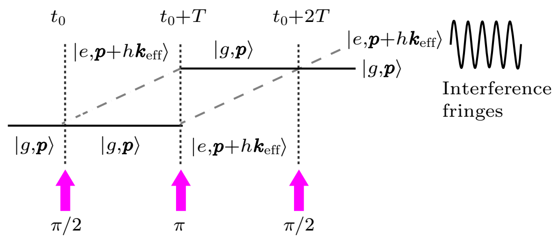

Fig. 1. Principle of a Mach–Zehnder type atom interferometer.

In our atom interferometer, a Doppler sensitive Mach–Zehnder (M-Z) configuration is used. Figure 1 shows the diagram of the M-Z interferometer. ^{85}Rb atoms are first cooled and trapped by a magneto-optical trap (MOT), and then manipulated via two-photon Raman transition of a three-level system.[29–31] The atomic wave packet is divided, reflected, and recombined coherently by a $\pi/2-\pi-\pi/2$ counter-propagating Raman pulse sequence. The first $\pi/2$ pulse drives atoms from the initial state $|g,\boldsymbol{p}\rangle$ to the superposition of states $|g,\boldsymbol{p}\rangle$ and $|e,\boldsymbol{p}+\hbar\boldsymbol{k}_{\rm eff}\rangle$, where $\boldsymbol{k}_{\rm eff}$ is the effective wave-vector of the Raman transition which equals to the sum of the wave-vector of two Raman lasers; after a free flight time T, a π pulse is applied, atoms in state $|g,\boldsymbol{p}\rangle$ are excited to

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**To whom correspondence should be addressed. Email: mszhan@wipm.ac.cn

$|e, \boldsymbol{p}+\hbar\boldsymbol{k}_{\rm eff}\rangle$ while those in state $|e, \boldsymbol{p}+\hbar\boldsymbol{k}_{\rm eff}\rangle$ are transferred to $|g, \boldsymbol{p}\rangle$; then after another free flight time T the second $\pi/2$ pulse is added, and the two wave packets interfere with each other when the $\pi/2-\pi-\pi/2$ sequence ends.

The population of final states can be described as

$$P_{e,g} = \frac{1}{2}[1 \pm \cos(\Delta\Phi)], \quad (1)$$

and the total phase shift $\Delta\Phi$ is

$$\Delta\Phi = \Delta\Phi_g - \Delta\Phi_{\rm Laser}, \quad (2)$$

where $\Delta\Phi_{\rm Laser}$ is the phase of Raman lasers and $\Delta\Phi_g$ is the phase shift due to the gravitational field. $\Delta\Phi_g$ depends on g in the way of

$$\Delta\Phi_g = k_{\rm eff} g T^2. \quad (3)$$

The experimental setup is shown in Fig. 2, which is similar to the atom interferometer we developed before,[29] but the interference region is now set to be vertical to form an atom fountain. The three pairs of cooling and trapping beams are in the [1,1,1] configuration, they also act as launching beams for atomic fountain. We firstly cool and trap about 3×10^8 atoms in the MOT within a time of 900 ms, then turn off the magnetic field. After 10 ms, atoms are launched by moving molasses; the frequencies of three upward laser beams are tuned with a value of $\nu_{\rm launch}$, while the frequencies of downward laser beams are tuned with a value of $-\nu_{\rm launch}$ at the same time. The relation between the launch velocity of the atoms $\upsilon_{\rm atom}$ and frequency shift $\nu_{\rm launch}$ is given by

$$\upsilon_{\rm atom} = \sqrt{3}/2\lambda\delta\nu_{\rm launch}. \quad (4)$$

In our experiment, the value of frequency shift is 2.1 MHz, which corresponds to a launch velocity of 2.8 m/s. Atoms are launched to a height of 410 mm, and the free flight time is 500 ms. Temperature of the atom cloud is measured by time-of-flight (TOF) signal, and the average temperature is 30 µK.

During the free flight time, we apply the state-selective laser pulses, Raman laser pulses, and probe laser pulse successively. Firstly, enough atoms should be prepared in the initial state $[F=2,\ m_F=0]$. When atoms move out the MOT area, launching beams are turned off ($t=0$ ms), and repumping beam is still on for 2 ms, so almost all atoms are pumped to state $F=3$. At $t=90$ ms, atoms enter a strong magnetic field area with a bias field of 300 mG, and a velocity-selective Raman π pulse transfers atoms in state $[F=3,\ m_F=0]$ to $[F=2,\ m_F=0]$ with a narrow velocity distribution. The bias field is turned off after the state selection, and a laser beam resonant with transition $F=3\rightarrow F'=4$ is added to blow away the unwanted atoms. After this sequence, only atoms in state $[F=2,\ m_F=0]$ with vertical temperature lower than 100 nK are maintained. When the atoms enter the interference region which is well shielded for magnetic field at $t=190$ ms, Raman pulses sequence $\pi/2-\pi-\pi/2$ are implemented with a variable time interval of Tbetween pulses, and a Doppler sensitive M-Z interferometer is accomplished. At $t=500$ ms, a probe beam nearly resonant with transition $F=3\rightarrow F'=4$ is applied and the population of state $F=3$ is recorded by a detector with laser induced fluorescence (LIF) method. A computer is used to acquire and process the data. An interference fringe appears when the population signal vs phase difference of Raman lasers is plotted.

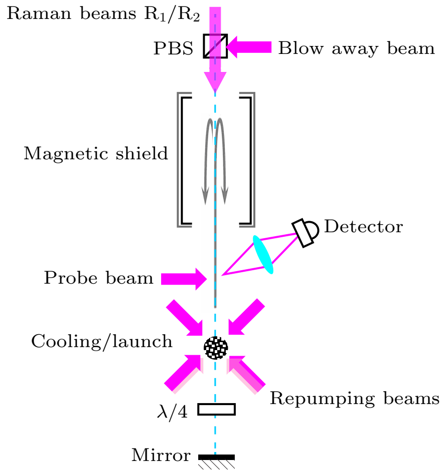

Fig. 2. Experimental setup. PBS: polarization beam splitter cube, $\lambda/4$: quarter-wave plate.

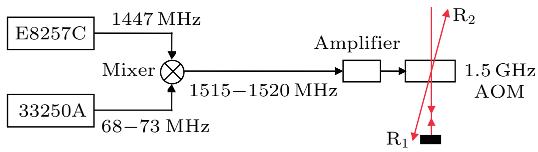

Fig. 3. Arrangement of the Raman laser system. AOM: acousto-optical modulator.

The Raman beams are generated by a 1.5 GHz AOM (Brimrose GPF-1500-200-.780), the ±1 order outputs of the AOM are used as Raman beams R_1 and R_2 respectively, the arrangement detail is shown in Fig. 3. The rf signal is supplied by a microwave synthesizer, an analog signal generator (Agilent E8257C PSG) provides 1447 MHz as a local oscillator, and a low frequency signal generator (Agilent 33250A) supplies 70 MHz signal. Both rf signals are referenced to a hydrogen clock (SOHM-III). The 1447 MHz rf signal serves as a reference frequency, and we sweep the low frequency rf signal to compensate for the Doppler shift due to the gravitational field. The Raman beams are guided to the viewports of the vacuum chamber by single-mode polarization-maintaining fibers (PMF), and the pulse width of Raman beams are controlled by an AOM. The Raman beams are linear polarized and collimated by a collimator, they enter the vacuum chamber from the top window and retro-reflected by a mirror located under the bottom window. A quarter-wave phase plate is placed above the mirror to change the polarization of retro-reflected beams, thus the lin⊥lin configuration of Raman beams are formed to drive Doppler-sensitive Raman transition. The total power of Raman beams is 12 mW, the power ratio of Raman beams R_1 and R_2 is tuned to 3.6 : 1 to minimize unwanted ac Stark shifts. The width of the sate-selective pulse is 50 µs, and the π pulse is 40 µs.

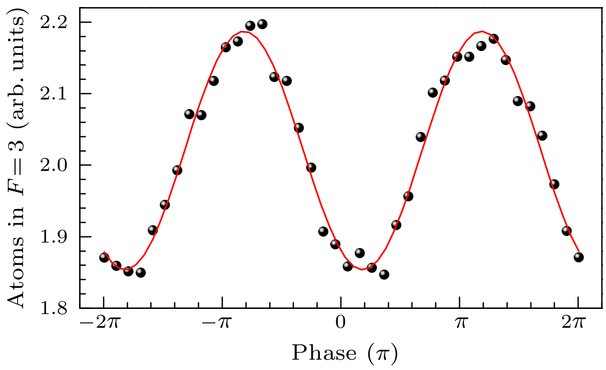

Fig. 4. Interference fringes exhibited as a function of relative population to the phase of Raman lasers. Interrogation time between pulses is $T = 150$ ms, 4 times average in 236 s, the uncertainty of phase is 24.4 mrad, corresponding to a resolution of 7×10^{-9} g.

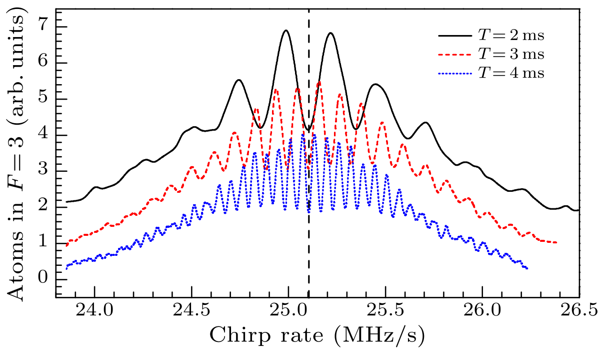

Fig. 5. Ramsey fringes with different T. The center points (indicated with vertical dashed line) do not vary with T, and the chirp rate of this point corresponds to total effect of local gravity and system errors.

In order to obtain the interference fringe, we changed the chirp rate of each point and recorded 40 points for each cycle of 4π phase shift. This was realized by controlling the signal generator (Agilent 33250A) via a LabVIEW software. Population vs chirp rate shows an interference fringe. Information of local gravity, such as absolute value of g, is included in the interference fringes. Equation (3) shows that increasing the time T will improve the measurement resolution. However, if the time T is too long, the contrast of interference fringes will become poor due to vibrational noise and other system effects. To avoid the random vibration, the whole experimental apparatus was mounted on a vibration isolated optical table (Newport RS-4000 floating on I-2000 legs). We obtained the interference fringes under different T. The present value of T in our experiment is 150 ms (shown in Fig. 4.). Within an integration time of 236 s, the best resolution is 7×10^{-9} g, corresponding to a sensitivity of 1.1×10^{-7} g/Hz$^{1/2}$.

When the chirp rate of the Raman laser equals to the Doppler shift due to the gravity, the phase shift of Raman beams will exactly compensate for the gravitational phase shift. We obtained the Ramsey fringes with different T, and the experimental data are shown in Fig. 5. The chirp rate corresponding to the center point (indicated by the dashed line in Fig. 5) of the Ramsey fringes does not depend on T, and we can deduce the absolute g value from the equation

$$\Delta\Phi = \boldsymbol{k}_{\rm eff} \cdot \boldsymbol{g}T^2 - 2\pi\alpha T^2 = 0, \qquad (5)$$

where α is the chirp rate of the frequency difference between two Raman beams and the value is about 25.1 MHz/s in our experiment. By using a relative gravimeter (Scintrex CG-5), we compared the absolute gravity with 10^{-8} g accuracy at location of No.3053 gravity station, and obtained a difference of 1.5×10^{-7} g between our measured value and the referenced value at our laboratory.

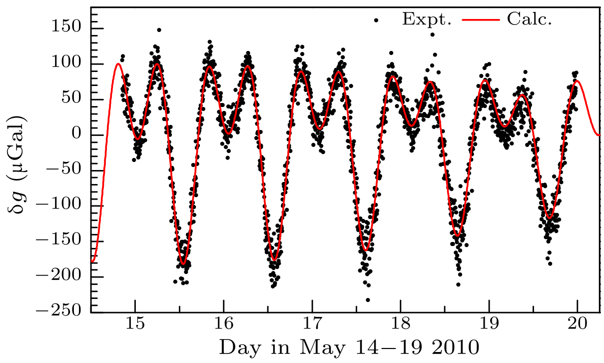

Fig. 6. Gravity data for 123 h measured at Wuhan from 14 May to 19 May 2010.

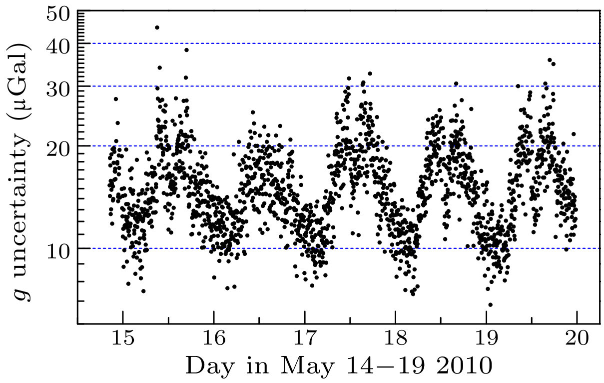

Fig. 7. The uncertainty of gravity data at Wuhan from 14 May to 19 May 2010.

The main problem for precision measurement is how to analyze the systematic errors. We have analyzed some system effects, such as the dependence of Raman transition on magnetic field,[32] the quadratic Zeeman shift,[33] the ac Stark shift, ^{85}Rb D_2-wavelength, vertical alignment and retro-reflection alignment, which are all found be below 10^{-7} g. More precision measurements will be carried out by considering other systematic errors and making calibration with and comparison to more accurate gravimeters.

Usually, local gravity changes with time due to the tidal effects. Similar to other gravimeters, atom interferometers can be used to observe the tidal phenomenon by monitoring the local gravity continuously. We measured the tidal effects using this compact atom interferometer. The gravity data in 123 h is shown in Fig. 6. The uncertainty of each interference fringe data point is plotted in Fig. 7, from which we can see that during the daytime the noise is much larger, thus the major error source should be the vibrational noise due to the environmental human activities near the laboratory.

By averaging all the data in Fig. 6 (tide subtracted from theoretical value), a sensitivity of 2.0×10^{-7} gHz$^{-1/2}$ can be deduced (see Table 1).

Table 1. List of different atom gravimeters.[37]

Atom gravimeter	Configuration	Sensitivity (gHz$^{-1/2}$)	Accuracy (g)	References
Standford-1999	Fountain	2×10^{-8}	$(7 \pm 7) \times 10^{-9}$	[3,4]
Standford-2008	Fountain	1.1×10^{-8}		[19]
LNE-SYRTE-2006	6-axis	1.5×10^{-6}		[8]
LNE-SYRTE-2008	Release	1.4×10^{-8}	$(4.3 \pm 6.4) \times 10^{-9}$	[5,34]
LNE-SYRTE-2010	Release	1.7×10^{-7}		[35]
ONERA-2009	Release	2.8×10^{-6}	7.5×10^{-6}	[36]
WIPM-2010	Fountain	2.0×10^{-7}	1.5×10^{-7}	This work

In summary, we have demonstrated a precision measurement of gravity by a compact cold atom interferometer. The absolute value of local gravity acceleration at our laboratory is measured with a sensitivity of 2.0×10^{-7} gHz$^{-1/2}$. The accuracy of the absolute value is about 1.5×10^{-7} g compared to the reference value. The tidal phenomenon was observed by monitoring the local gravity continuously over 123 h using this atom interferometer. Further assessment of the atomic gravimeter to characterize the absolute sensitivity is under way.

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