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REVIEW ARTICLE

Experimental progress in gravity measurement with an atom interferometer

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Precisely determining gravity acceleration g plays an important role on both geophysics and metrology. For gravity measurements and high-precision gravitation experiments, a cold atom gravimeter with the aimed resolution of 10^{-9}g/Hz$^{1/2}$ (1 g=9.8 m/s^2) is being built in our cave laboratory. There will be four steps for our ^{87}Rb atom gravimeter, Magneto–Optical Trap (MOT) for cooling and trapping atoms, initial state preparation, $\pi/2$–π–$\pi/2$ Raman laser pulse interactions with cold atoms, and the final state detection for phase measurement. About 10^8 atoms have been trapped by our MOT and further cooled by moving molasses, and an atomic fountain has also been observed.

Keywords gravity measurement, atom interferometry

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Contents

1 Introduction

The acceleration of gravity g is an important quantity of Earth, which varies with time and space. Precise measurements of g are of interest to wide applications on finding natural sources, navigation, and other scientific fields [1]. Instruments that measure gravity come in many different forms and can be distinguished into relative gravimeters and absolute gravimeters. Relative gravimeters are usually spring type or superconducting type with very high sensitivity of 10^{-10}g/Hz$^{1/2}$ and 10^{-12}g/Hz$^{1/2}$, respectively [2]. Relative gravimeters are very sensitive to relative changes in gravity and can map spatial variation or time-dependent changes in gravity with high precision. Their main shortage is that their readings are only relative and need to be calibrated with absolute gravimeters.

Absolute gravimeters can give the absolute value of acceleration due to gravity by means of monitory of a freely falling object. There are two kinds of absolute gravimeters up to date. One is freely falling corner-cube gravimeter [3], such as FG-5, which use a laser interferometer to monitor the motion of the corner cube. FG-5 has reached a resolution of 5×10^{-8}g/Hz$^{1/2}$, and its accuracy can reach 2×10^{-9}g [2, 3]. The measurement accuracy of FG-5 is currently limited by a number of systematic effects, not all of them fully understood [3]. The other type is cold atom interferometry gravimeter [2, 4, 5], which instead of freely falling corner cube, measures the gravity acceleration by dropping cold atoms.

The cold atom interferometry gravimeter was first used by Chu in 1992 [4], sodium atoms were lunched and freely falling in an atomic fountain, and the acceleration of sodium atoms was measured by atom interferometry method. The cesium atom gravimeter in Chu's group has reached a resolution of 2×10^{-8}g/Hz$^{1/2}$, and an accuracy of 3×10^{-9}g [2] in 2001. Because of the high repetition rates and high potential accuracy, atom gravimeter is concerned by many groups in the world after that [6, 7]. Compared to corner cube, atoms are good test mass to avoid some systematic effects, for example, rotation of corner cube [3] limits the accuracy of FG-5. "I think it is clear that the methods of atom interferometry will be used in future commercial gravimeters" said by Fall [1] who is one pioneer of absolute gravimeters. Atom interferometry gravimeter is also widely used to determine the gravitational constant G [7, 8] and test the equivalence of principle [9]. For the future using, navigation and measure gravity in space with atom gravimeter will be a good choice [10, 11].

To measure absolute gravity acceleration, a cold atom interferometry gravimeter is being built in our cave laboratory since 2006. Our goal is to build a cold ^{87}Rb atom interferometry gravimeter with resolution of 1×10^{-9}g/Hz$^{1/2}$ and use it for precision gravitational experiments, such as determining the gravitational constant G, testing Newton's inverse square law, and testing equivalence principle *et al.*. The principle of atom gravimeter and experimental progress will be introduced in this paper.

2 Principle of atom interferometry gravimeter

Optical interferometers established a tradition of beautiful experiments and precise measurements. It has long been a tempting idea to use matter waves in interferometry. Atoms possess many internal states, which are easily manipulated by external electromagnetic field. Moreover, the technologies of laser cooling and trapping allow extraordinary long measurement time so that atom interferometers with high precision can be constructed. The atom interferometers first demonstrated by Canal and Mlynek [12] and Keith [13] *et al.* in 1991 were based on diffraction of atoms with microfabricated structures. In the same year, atom interferometers based on optical pulse were reported by Riehle *et al.* [14] and Chu [15]. Here, we introduce the principle of atom interferometer demonstrated by Chu.

We first consider an atom with only two energy levels. The Hamiltonian for a two-level atom coupled to an electromagnetic field of a laser without spontaneous emission is

$$\hat{H} = \hbar\omega_e |e\rangle\langle e| + \hbar\omega_g |g\rangle\langle g| - \boldsymbol{d}\cdot\boldsymbol{E} \tag{1}$$

where ω_e and ω_g are the eigen frequencies of excited state $|e\rangle$ and ground state $|g\rangle$, and $\boldsymbol{d}$ is the electric dipole moment of atom. The electromagnetic field is

$$\boldsymbol{E} = \boldsymbol{E}_0\cos(\omega_L t + \Phi_0) \tag{2}$$

The time evolution of atom's state

$$|\Psi(t)\rangle = a_e(t)|e\rangle + a_g(t)|g\rangle \tag{3}$$

is given by Schrödinger equation:

$$\mathrm{i}\hbar\frac{\partial}{\partial t}|\Psi(t)\rangle = \hat{H}|\Psi(t)\rangle \tag{4}$$

With the rotating wave approximation, the evolution operator $\hat{U}$ can be solved from Eqs. (1) and (4):

$$\hat{U} = \begin{pmatrix} \cos\Omega_r\tau/2 & -\mathrm{i}\mathrm{e}^{-\mathrm{i}\Phi_0}\sin\Omega_r\tau/2 \\ -\mathrm{i}\mathrm{e}^{\mathrm{i}\Phi_0}\sin\Omega_r\tau/2 & \cos\Omega_r\tau/2 \end{pmatrix} \tag{5}$$

where $\Omega_r = \sqrt{|\Omega_{eg}|^2 + \delta^2}$, Rabi frequency $\Omega_{eg} = -\langle e|\boldsymbol{d}\cdot\boldsymbol{E}_0|g\rangle/\hbar$, $\tau = t - t_0$ is the interaction time, and we suppose that the detuning $\delta = \omega_L - (\omega_e - \omega_g) = 0$. The $\pi/2$ and π pulse correspond to pulse with an interaction time of $\Omega_r\tau = \pi/2$ and $\Omega_r\tau = \pi$, respectively. Now, we can rewrite the atom's final state $|\Psi(t)\rangle$ as

$$|\Psi(t)\rangle = \hat{U}|\Psi(t_0)\rangle \tag{6}$$

where $|\Psi(t_0)\rangle$ is the initial state of atom.

We can see that if an atom is in the initial state of $|g\rangle$, after exposing to a $\pi/2$ pulse, the probabilities of finding final state in $|g\rangle$ and $|e\rangle$ are 50% respectively, just like a beam splitter in an optical interferometer; after exposing to a π pulse, atom will be put to excited state $|e\rangle$ with a probability of 100% and like a mirror in an optical interferometer.

Actually, the three-level atom underlying two-photon stimulated Raman transition [16] is used for atom interferometer. As shown in Fig. 1, the Hamiltonian for this three-level atom coupled to two laser fields with a frequency of ω_1 and ω_2, respectively, is

$$\hat{H} = \frac{P^2}{2m} + \hbar\omega_e|e\rangle\langle e| + \hbar\omega_i|i\rangle\langle i| + \hbar\omega_g|g\rangle\langle g| - \boldsymbol{d}\cdot\boldsymbol{E} \tag{7}$$

where P is the momentum of the atom, $\boldsymbol{E}$ can be considered as the superposition of two individual laser fields:

$$\boldsymbol{E} = \boldsymbol{E}_1\cos(\omega_1 t - k_1 z + \Phi_1) + \boldsymbol{E}_2\cos(\omega_2 t - k_2 z + \Phi_2) \tag{8}$$

Moreover, we can define $\omega_{\text{eff}} = \omega_1 - \omega_2$, $\boldsymbol{k}_{\text{eff}} = \boldsymbol{k}_1 - \boldsymbol{k}_2$, and $\Phi_{\text{eff}} = \Phi_1 - \Phi_2$.

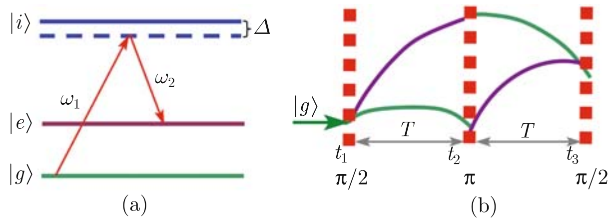

Fig. 1 **(a)** Three-level system coupled to two laser fields; **(b)** Atom interferometry with $\pi/2$–π–$\pi/2$ pulse.

The atom absorbs a photon with frequency ω_1 pumped to state $|i\rangle$ first and then stimulated to emit one photon with frequency ω_2. The large detuning Δ of laser frequency from the interim state $|i\rangle$ greatly suppresses the spontaneous emission, so this there-level system can effectively look as a two level system, and the evolution operator Eq. (5) can be used to describe the interferometry process, and with effective Rabi frequency,

$$\Omega_{\rm eff} = \frac{\Omega_1 \Omega_2}{2\Delta} \tag{9}$$

where Ω_1 and Ω_2 are the single photon Rabi frequency corresponded to each transition.

The π/2–π–π/2 type atom interferometer shown in Fig. 1(b) can be described using five evolution operators: $\hat{U}_{\pi/2}$, $\hat{U}_{\rm free1}$, $\hat{U}_{\pi}$, $\hat{U}_{\rm free2}$, and $\hat{U}_{\pi/2}$. The final state $|\Psi(t)\rangle$ after three laser pulses is

$$|\Psi(t)\rangle = \hat{U}_{\pi/2}\hat{U}_{\rm free2}\hat{U}_{\pi}\hat{U}_{\rm free1}\hat{U}_{\pi/2}\,|\Psi(t_0)\rangle \tag{10}$$

If the atoms freely fall in gravity field with an initial state of $|\Psi(t_0)\rangle = |g\rangle$, and the time interval of laser pulses is T, the probability for final state in $|e\rangle$ is

$$P = \frac{1}{2}[1 - \cos(\Delta\Phi - \boldsymbol{k}_{\rm eff}\cdot \boldsymbol{g}T^2)] \tag{11}$$

where $\Delta\Phi = 2\Phi_{\rm eff2} - \Phi_{\rm eff1} - \Phi_{\rm eff3}$, $\Phi_{\rm eff1}$, $\Phi_{\rm eff2}$ and $\Phi_{\rm eff3}$ are the Raman beams' initial phase $\Phi_{\rm eff}$ for every laser pulse, and $\Phi_{\rm eff2} = \Phi_{\rm eff1} + \int_{t_1}^{t_2} \omega_{\rm eff}{\rm d}t$. Suppose that Raman beams are exactly along vertical direction, and atoms are launched vertically too, Eq. (11) should be changed to

$$P = [1 - \cos(\Delta\Phi - k_{\rm eff}gT^2)]/2 \tag{12}$$

where $\boldsymbol{k}_{\rm eff} = \boldsymbol{k}_1 - \boldsymbol{k}_2 \approx 2\,|k_1| = 1.6\times10^7$/m. For a typical interferometer time T=160 ms, yielding a phase shift due to Earth's gravity acceleration g of $\Delta\Phi_g = k_{\rm eff}gT^2 = 4.0\times10^6$rad. We can measure g with a sensitivity of 1×10^{-9}g/Hz$^{1/2}$ if the atom interferometer phases noise at level of 4 mrad/Hz$^{1/2}$.

3 Experimental progresses

The Magneto–Optical Trap was described everywhere [17–19]. Our atom gravimeter is schematically shown in Fig. 2. The trapping laser (Toptica TA100) is locked to the ^{87}Rb D2 line crossover peak $5S_{1/2}, F = 2 \rightarrow 5P_{3/2}$, $F=2$ and $F=3$ by saturation absorption method. When loading the atoms to MOT, the frequency of trapping beam is set to 23MHz red detuning from the resonance $5S_{1/2}, F=2 \rightarrow 5P_{3/2}, F=3$ by AOM (AA, MT110-B50A1-IR) frequency shifter, while in the moving molasses time, the detuning is increased to 60 MHz. The trapping laser is separated into three pairs by two fiber system, collimated to a diameter of 22 mm and transmitted to the vacuum chamber by six single-mode polarization-maintaining fibers. Each pair is σ^+–σ^- polarized, and the power of every trapping beam is (27±1) mW, while the repumping laser (Toptica DL100) is locked to the transition $5S_{1/2}, F = 1 \rightarrow 5P_{3/2}, F = 2$ by modulation transfer method [20, 21] and sent to the vacuum chamber overlapping with one of trapping beams.

The aluminum MOT chamber has (1,1,1) configuration with vacuum of 10^{-10} Torr, and the top and bottom windows are prepared for Raman beams. The MOT coils with 3 A current can generate 8 G/cm magnetic gradient in the MOT center. Three pairs of Helmholtz coil are used to compensate the earth magnetic fields. ^{87}Rb atoms are released from a rubidium dispenser.

When the dispenser current is 4.3 A, about 3×10^8 atoms are trapped by the MOT after 1 second loading time. The magnetic field is shut off at the end of loading, and atoms are lunched by down shifting the frequency of the upper three trapping beams by 6 MHz. Moving molasses with 1.4 ms are used to further cooling the atoms after 1.5 ms launching. The atom cloud is accelerated to 4.08 m/s after moving molasses. We use time-of-flight (TOF) method [22] to determine the temperature of the atom and the fountain's parameters. The TOF signal is recorded by fluorescence detection method in the detection region.

We have schematically realized the atomic fountain for the first step of atom gravimeter. State preparation and Raman pulses interferometry are next key steps for atom gravimeter.

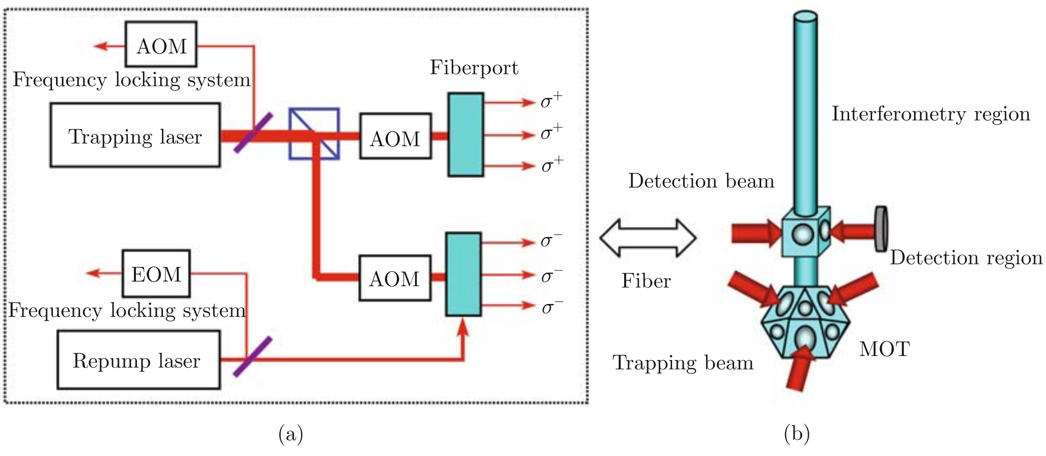

Fig. 2 **(a)** Schematic diagram of optics for atomic fountain; **(b)** Schematic diagram of vacuum chamber for atom gravimeter.

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