Cold atom space clock with counter-propagating atoms

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We discuss the feasibility of realizing a cold atom space clock with counter-propagating cold atoms in microgravity. The design of the space clock is based on an atomic beam clock with Ramsey cavity, except that magneto-optical trap (MOT) is placed at each side. Cold atoms are launched simultaneously from the MOTs at both sides of the clock and they move at the counter-direction towards each other. The velocity of the launched atoms is precisely controlled to Ramsauer-Townsend resonance so that no additional collision frequency shift takes place. Such configuration can efficiently cancel the frequency shift resulting from cavity phase shift and increase the signal-to-noise ratio (SNR).

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In 1955, the first atomic frequency standard that used a Cs beam excited by a separated oscillatory field was completed by Essen *et al.*[1]. The approach was proposed by Ramsey in 1950[2]. In the Ramsey atomic clock, an atomic beam is formed in an oven and allowed to drift freely in high vacuum into an interaction region formed by a microwave structure called the Ramsey cavity. The structure generally has a U-typed waveguide. This arrangement creates two short microwave interaction regions of length ℓ, separated by a relatively large distance L. After traversing the first interaction region, the atoms are exposed to the microwave field for a short time, which depends on L, and then enter the second interaction region. Similar to the technique of magnetic resonance, the transitions of atoms are excited between two special levels. The advantage of the Ramsey-type atomic clock is that interferences take place between the excitation in the two interaction regions, leading to a series of fringes called "Ramsey fringes". A narrow resonance can be obtained by a factor of the order of L/ℓ.

In experiment, maintaining the phases of microwave between two interaction regions in an accurate and consistent manner is very difficult. A small unwanted phase shift may be caused by an asymmetry in the Ramsey cavity construction, and then the central fringe is distorted. This shift is the so-called "cavity phase shift". Cancelling the cavity phase shift in theory or minimizing it for improving the accuracy of the Ramsey-type atomic clock is necessary.

In a classical thermal cesium clock, a beam of atoms effuses from an oven and passes through a state-selecting magnet, then subsequently passes through a Ramsey microwave cavity and is detected[3]. The velocity of thermal atoms can be as slow as 95 m/s, and the line width of clock transition is typically around 60 Hz, as Physikalisch-Technische Bundesanstalt (PTB) Cs frequency standards apply[3]. To test the cavity phase frequency shift, in PTB's primary clock CS2, an oven and detector is placed at each end so that an alternate operation of the atomic beam in opposite directions can be performed[4].

In 1954, Zacharias attempted to obtain an even narrower separated oscillatory field resonance in a "fountain" experiment[5,6]. The most important improvement in the fountain clock is the use of one interaction field instead of two regions. Atoms interact with the one interaction region twice in the track of up and down, and interferences take place between the two rounds of interaction. Thus, the cavity phase shift can be cancelled in theory. Unfortunately, the experiment failed due to the very slow atoms scattered away as they emerged from the thermal source.

The advent of laser cooling techniques has opened the door to a new approach on the fountain clock[6]. Atoms are first captured and cooled in a magneto-optical trap (MOT), and then launched upward by a technique called moving molasses. The width of the Ramsey fringe for a fountain is determined by $\Delta\nu = 0.25\sqrt{g/2H}$, where g is the gravitational acceleration, and H is the maximum height of the launched atoms. Typically, for a cold atom fountain clock, the width of the central Ramsey fringe is 1 Hz, which corresponds to $H = 0.3$ m. A narrower width is possible but technically difficult. For example, a 0.1-Hz width requires $H = 30$ m, which is impractical.

Soon after the success of the fountain clock, people noticed that even a narrower width can be realized in a microgravity environment[7]. In microgravity, the atoms move at constant velocity after they are launched from a MOT, which means that the slower velocity of the launched atoms leads to longer interrogation time or narrower width of the central Ramsey fringe. In a microgravity environment, however, the design of the fountain clock cannot be adopted in the cold atom space clock, and the Ramsey cavity structure is recalled again. Therefore, the cavity phase shift should be examined again, especially for a cold atom space clock with high accuracy and stability.

In a cold atom space clock, the PHARAO[7] for example, cold atoms are launched from an optical molasses at a velocity as low as 5 cm/s, and a 0.1-Hz width of central Ramsey fringes is predicted. The expected stability is $10^{-13}/\sqrt{\tau}$, where τ is the integration time, and the accuracy is up to 10^{-16}. For such high stability and accuracy, the phase shift of the space clock's Ramsey cavity becomes more important. Certainly, the application of PTB's CS2 clock design in the space clock is possible, and the alternate operation of cold atoms in the opposite direction gives the information on the cavity phase shift, however, this design wastes precious space resources.

In this letter, we propose a new type of space clock whose design is similar to that of the PTB's CS2[4], but with a completely new operation mode. This new type of space clock aims to cancel the frequency shift due to the phase difference of the Ramsey cavity and to increase the signal-to-noise ratio (SNR), thus reducing the technical difficulties of the design and improving the performance of the space clock. As shown in Fig. 1, MOT and a detection region are placed at each end. Cold atoms are launched simultaneously from both MOTs in the opposite direction toward each other. Assuming cloud A denotes the cold atoms launched from the left MOT and cloud B from the right MOT, cloud A collides with cloud B at the center of the Ramsey cavity after they pass through the first interaction region of the cavity.

In atom-atom collisions, if the atoms are treated classically as hard balls, the calculated-cross section is independent of the atomic energy. In quantum mechanics, however, the atoms are considered to present a dipole-dipole interaction of the typical atomic dimensions for the scattering among atoms. The solution of the Schrödinger equation for two dipole-dipole potentials shows that the cross-section in atom-atom collisions has a minimum at some specific energies. This is a simple illustration of the Ramsauer-Townsend resonance[8]. At this resonance, the atoms are transparent with one another when they collide, and the frequency shift led from the collisions becomes null. Legere *et al.* measured the *s*-wave frequency shift using juggling ^{133}Cs and ^{87}Rb fountain clock[9−11]. The first Ramsauer-Townsend shift null for ^{87}Rb takes place at alternate launch time delays of $\Delta t = 22$ ms between two cold atom balls, corresponding to the velocity $v_{\rm RT} = g\Delta t/2 = 10.78$ cm/s of each ball propagating at the opposite direction. At this velocity, the collision between clouds A and B does not contribute an additional frequency shift. For the scattering of identical particles, *p*-wave scattering does not contribute an additional frequency shift.

We assume that the interrogation length of the Ramsey cavity is $L = 52.5$ cm, which gives the interrogation time $T_{\rm RT} = L/v_{\rm RT} = 4.9$ s when cloud A or B moves at the Ramsauer-Townsend velocity $v_{\rm RT}$. This interrogation time corresponds with the linewidth of the central Ramsey fringe at $\Delta\nu = 0.1$ Hz. If the number of detected atoms is $N = 10^6$, we have the Allan variance

$$\sigma_y(\tau) = \frac{\Delta\nu}{\pi\nu_0\sqrt{N}}\sqrt{\frac{T}{\tau}} = 1.5\times10^{-14}/\sqrt{\tau}, \qquad (1)$$

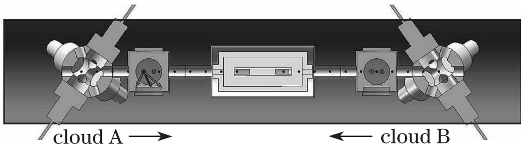

Fig. 1. Schematic diagram of cold atom space clock with counter-propagating atoms.

where $T = 10$ s, which includes time for the preparation of the cold atoms, state selection, interrogation time, and detection; $\nu_0 = 6.835$ GHz is the frequency of the clock transition of ^{87}Rb, and τ is the integration time. If we do not consider the phase shift of the Ramsey cavity, we can average the detected atoms from both clouds A and B such that $N = 2\times10^6$, which leads to the reduction in Allan variance by a factor of $\sqrt{2}$ from Eq. (1), which is $\sigma_y(\tau) = 1.1\times10^{-14}/\sqrt{\tau}$.

On the other hand, with atoms' counter-propagation through a Ramsey cavity, the cavity phase shift can be accurately measured, so the frequency shift can be adjusted away from the error budgets of the clock. Alternately the frequency shift due to phase differences in the cavity can be cancelled if we average the signals from both clouds A and B. Assuming a phase difference $\Delta\varphi$ between two zones of the Ramsey cavity, we can easily obtain the probability of finding the two-level system in the excited state as[12]

$$p_{\rm A} = \frac{1}{2}\sin^2\Omega t\{1+\cos[2\pi(\nu-\nu_0)T_{\rm RT}+\Delta\varphi]\}, \qquad (2)$$

$$p_{\rm B} = \frac{1}{2}\sin^2\Omega t\{1+\cos[2\pi(\nu-\nu_0)T_{\rm RT}-\Delta\varphi]\}, \qquad (3)$$

where $p_{\rm A}$ and $p_{\rm B}$ are the probabilities for clouds A and B, respectively, Ω is the Rabi frequency, and t is the interaction time between atoms the and microwave. Generally, the phase difference $\Delta\varphi$ shifts the center of the Ramsey fringe by

$$\frac{\Delta\nu_\varphi}{\nu_0} = -\frac{\Delta\varphi}{2\pi\nu_0 T_{\rm RT}} \qquad (4)$$

in $p_{\rm A}$ and $-\Delta\nu_\varphi/\nu_0$ in $p_{\rm B}$. Typically, the phase difference of a U-type Ramsey cavity can be controlled below a few hundred μrad. If we take the phase difference $\Delta\varphi = 500$ μrad for example, we have $\Delta\nu_\varphi/\nu_0 = 2.3\times10^{-15}$. Thus in order to get accuracy of a few 10^{-16}, the frequency shift due to the phase difference of the cavity must be carefully considered.

If we take the average over the probability of clouds A and B, we have

$$p = \frac{p_{\rm A}+p_{\rm B}}{2} = \frac{1}{2}\sin^2\Omega t[1+\cos 2\pi(\nu-\nu_0)T_{\rm RT}\cdot\cos\Delta\varphi]. \qquad (5)$$

Obviously, in p, the phase difference of the cavity does not contribute any frequency shift, but the width of the central Ramsey fringe has been broadened to

$$\Delta\nu_p = \Delta\nu + 2\Delta\nu_\varphi. \qquad (6)$$

Typically, the phase difference of the Ramsey cavity is around a few hundred μrad[3]. From Eq. (4), we have $\Delta\nu_\varphi \approx 1.6\times10^{-5}$ Hz when $\Delta\varphi = 500$ μrad for example, which can be neglected in Eq. (6). Therefore the width broadening due to the average of the signal from both counter-propagating atoms can be neglected in the Allan variance given in Eq. (1). The collision between clouds A and B, due to each cloud moves at the Ramsauer-Townsend velocity, does not contribute an additional frequency shift. The frequency shift due to the cavity phase difference in our system can be cancelled without entailing additional costs.

In addition, our design has a very important function for reducing the noise of the interrogation time due to vibrations in the space craft and variations of residual microgravity in the atoms' propagating direction. This feature was first found by Fertig *et al.* in the design of a microgravity atomic clock with double Ramsey cavity[13]. Fertig's design has two Ramsey cavities located at both sides of a MOT, and cold atoms are launched alternative to each Ramsey cavity. Since the alternatively launching of cold atoms in the opposite direction does not happen at the same time, these cold atoms do not sense the same vibration and residual microgravity. In our design, however, with the counter-propagation of atoms through the same cavity at the same time, the detected signals of clouds A and B behave oppositely and simultaneously. Therefore the effect of vibrations and variations of the microgravity can be removed by the averaged signal p.

Our design has some unique features especially suitable for certain experiments. For example, if the velocity of launched atoms varies, the cross-section of atom-atom scattering can be measured by our space clock even more precisely than by the juggling fountain clock. Such measurement can give detailed data for atom-atom scattering and can test the fundamental principle of quantum mechanics.

A further analysis on the influence of cold atom density, cold atom temperature, geometry of cold atom cloud etc, will be done in order to design such a clock.

In conclusion, we have proposed a new type of cold atom space clock with counter-propagating atoms. The cold atoms move at Ramsauer-Townsend velocity so that the collision between counter-propagating atoms becomes null. We have pointed out that this null collision cross-section can cancel the frequency shift led from the phase difference of the Ramsey cavity, as well as increase the SNR. We have estimated the Allan variance of such a space clock at $1.5 \times 10^{-14}/\sqrt{\tau}$. Furthermore, our design of the cold atom space clock can efficiently remove the noise due to vibration and residual microgravity of the space craft, thereby reducing the requirement of the space environment. This kind of space clock will facilitate a new method to test fundamental physics.

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