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# Possible Improvements in the Precision of the Atom-interferometric Equivalence Principle Test by Reducing AC Stark Shift Uncertainty

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**Abstract**. We discussed possible improvement methods for a dual-species atom interferometry test of the weak equivalence principle (WEP) at the $10^{-12}$ level. The original research tested the WEP by comparing the acceleration difference of the free-fallen rubidium isotopes atom clouds. Based on the percent uncertainty presented from this test, AC stark shift is the most significant obstacle to improving precision. This article will discuss a precision-improving method to the original test by suppressing the background AC stark shift by centering the interferometry lasers to their "magic frequency." The expected improved precision of the uncertainty level is below the $10^{-18}$ level. Due to the limitation of instruments, we have yet to test this improving method in the actual measurement. Still, we analyzed the possible difficulties in practical usage and discussed solving strategies that correspond to the problems.

**Keywords:** Equivalence principle, AC stark shift.

## 1. Introduction

The weak equivalence principle is a critical foundation of Einstein's general relativity. EP's primary idea is the equivalence of inertial mass and gravitational mass. Einstein delivered these two mass concepts to explain the equivalence of acceleration in Galileo's gravity experiment, and these two concepts later emerge as a sizable piece of the general theory of relativity. Moreover, the violation of EP is also crucial to modern physics because the existence of the violation will become a breaking point in unifying gravity with other fundamental forces. Due to the significance of the EP and its violation, tests on the EP are considered the valuable subject.).

Atom-interferometric test on the EP is a possible direction for testing trivial violations due to its high sensitivity compared with the classical optic interferometer. Beyond the advantage of high sensitivity, atom interferometers can also help researchers in exploring the weak equivalence principle (WEP) in genuine quantum aspects [1]. Many kinds of atom-interferometer were designed and applied to this research field. For example, light pulse atom interferometers, designed based on the diffraction of atoms from standing waves, can be used to measure the gravitational acceleration difference in Rb isotopes and thus test the WEP (weak equivalence principle) in the atomic level [2]. Other than the standard ground-based laboratories' design, there also exist specifically designed atomic interferometers for the space environment, where researchers can apply the free fall text on WEP under the weightless condition

[3]. The dual-species test on rubidium isotopes prevails in the atom-interferometer test on WEP. All the example research mentioned above tests WEP by comparing the gravitational acceleration difference between the rubidium isotopes. In this article, we will also discuss the improvements in a dual-species atom interferometer test. This method is from a recent study where the result reaches the precision on the $10^{-12}$ level [4]. Even though the precision of this research is already an improvement compared with the classical interferometry test, there is still optimization potential. AC stark shift is the splitting and shifting that happened at the atomic level, caused by the resonance of the alternating external electric field. In this case, the main sources of the shift are lasers. By comparing the systematic uncertainties, we find the uncertainty caused by AC stark shift has the highest percentage of total uncertainties. Therefore, further suppression of uncertainty caused by AC stark shift is needed. We are going to show one feasible improving direction below.

## 2. Suppression of the shift

As described in [4], researchers have tried to modify the frequency of lasers to “magic frequency” to minimize the shift effect for both isotopes. In addition, they utilize an $8\hbar k$ off-resonant pulse to bind the AC shift and eventually have the induced acceleration beneath $2.7 \times 10^{-12}$, where the acceleration is calculated by.

$$\Delta\phi = nk\Delta \mathrm{g} T^2 \tag{1}$$

By modifying Eq.1 we can get

$$\Delta g = \Delta\phi\ (nkT^2)^{-1} \tag{2}$$

Here, the acceleration magnitude is proportional to that of the phase shift. According to the uncertainty table in [4], about 80% of the acceleration uncertainty is induced by AC shift. Therefore, if the residual AC stark shift could be suppressed, the overall acceleration uncertainty will be significantly reduced. With a later study [5], the residual AC stark shift could be decreased to a lower stage around $10^{-18}$. According to equation (2), it is feasible to expect the uncertainty of acceleration to decrease to a level of $10^{-18}$.

The main idea of this new study [5] is that in the actual experimental laser conditions, besides those expected spectral contents, other background spectral factors could also affect the result. The previous study [4] does not include the consideration of these background spectral factors, so its uncertainty level may be advanced by suppressing the background AC stark shift.

According to the method in [5], the major problem of controlling background AC stark shift is the stability of the light. A solution will be using an optical bandpass filter. Even though the result in [5] is particularly focusing on the background stark shift in the optical lattice clock, similar background shifts of lasers may also happen on the atomic interferometer. Therefore, comparable techniques in [5] may also improve this atomic interferometer case. Thus, controlling and suppressing background AC stark shift through appropriate filter choice is plausible.

Based on the reflection transfer function of Bragg gratings [5], the reflectivity is approaching the peak while the frequency is approaching the center frequency. As a result of such property, by adding additional volume Bragg gratings to the laser sources, the laser frequency can be better centered on the designed frequency and disposing of the extra background spectrum. Figure 1 shows the simplified experimental design. According to [5], the designed frequency should be the “magic frequency” so that the shift effect on both isotopes is under the minimized state.

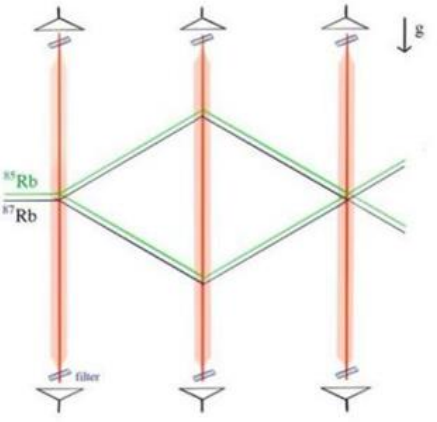

**Figure 1.** Simplified interferometer design. Red lines represent laser paths. Green and black line represents the path of isotopes. Additional volume Bragg gratings are applied to the laser source so they would be better cantered to the “magic frequency”.

## 3. Improvement of suppression method

Some difficulties and inadequacies could be consequential since we haven’t tested this possible amelioration in practice. One issue that might manifest within the realistic experimental surroundings is the choice of the Bragg grating. According to section 2, the bandwidth of the Bragg grating relies upon the detected spectra of the original setup. In [5], researchers used an optical spectrum analyzer to measure the background spectra, then used the result to design the needed Bragg gratings. However, since the original paper [4] does not involve the measurement of spectra, we can’t analyze the necessary parameters for gratings. Additionally, according to the previously mentioned [5], temperature, moisture, and other environmental elements can also affect reflectivity. However, these factors are not recorded in the original research. Therefore, we cannot include the considerations on those elements that could affect the level of uncertainty on the AC stark shift. Hence, by rebuilding the experiment, we can not only compare the uncertainty levels but also investigate the possible factor that could affect the reflectivity in the practical experimental condition.

Moreover, rebuilding the interferometer also solves another possible difficulty: the adjustment of the setup due to the additional effect of the grating filters. The Bragg grating filter will center the frequency but it will cause diffraction that may induce additional background shifts. One feasible method for this problem is settling a single optical fiber [5]. However, since the atomic interferometer has more laser sources than the setup in [5], the diffraction effect of gratings may have a more complicated situation which implies they will be harder to predict. The Atomic Farady filter may avoid the problem of reducing diffraction. Compared with the Bragg grating filter, the Atomic Farady filter is easier to apply while providing good stability on frequency [6]. However, the Atomic Farady filter, due to the structure of the cavity, has generally a higher reflectivity than the grating filter for all frequencies. It is hard to estimate which filter will have less effect until they are tested under practical experiments. For that purpose, in real experiments, we can use Ramsey pulses to measure and compare the AC shifts [7].

By precisely measuring and comparing the results using pulses, we can decide the best filter used for suppression. Beyond that, we may detect other subtle factors that affect the testing limit through precise measurements. But either way, rebuilding the interferometer will be necessary for both testing the subtle effects of the changes and comparing the filter’s choices. Through the methods described above, the uncertainty is expected to be improved from the $10^{-12}$ level to the $10^{-18}$ level, which is about 6 times smaller than the original result.

## 4. Conclusion

We have introduced a possible approach to the improvement of a current atom interferometer test on the EP. Due to the high percentage of AC stark shift effect in the previous study, the main concept of this new method is to keep suppressing the AC stark shift by reducing the shift caused by background optical content. In this improvement method, we use the Bragg Gratings to filter out the unexpected frequencies so the laser frequency can be stabilized around the "magic frequency". It will eventually cut down the background shift. We further discussed the difficulties of this new method in practice and their possible future solutions. Ultimately, the uncertainty caused by AC stark shift is expected to be decreased to the $10^{-18}$ level, and the expected total systematic uncertainty of the equivalence principle test is decreased by 80% to $0.7 \times 10^{-12}$.

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