Relationship measurement between ac-Stark shift of $^{40}Ca^{+}$ clock transition and laser polarization direction*

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Ac-Stark shift of atom levels is caused by an ac-electromagnetic field. As an electromagnetic wave, laser light does induce ac-Stark shift. It is proved experimentally that if the light is linearly polarized, the dynamic polarizability changes with polarization direction. The polarization direction of the linearly-polarized laser is tuned by 720°, and the ac-Stark shifts of the $4S_{1/2,\, m=\pm1/2} \rightarrow 3D_{5/2,\, m=\pm1/2}$ clock transitions in $^{40}Ca^{+}$ are measured in steps of 10°. The frequency shifts change with laser polarization in a periodical manner and have values opposite to each other.

Keywords: clock transition, ac-Stark shift, laser polarization direction

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1. Introduction

Polarizability is an intrinsic property of atoms, which determines how the atoms respond to an external field dynamically. Studying the polarizability of atoms is indeed helpul in many fields.[1–17] Research on the dynamic polarizability of atoms or ions will provide knowledge of the magic wavelength[1–8] corresponding to relevant transitions. Blackbody shift of the clock transition frequency can be evaluated through its static polarizability.[9–13] The dynamic polarizability is also helpful in constructing the long-range-potential which is crucial in Bose–Einstein condensation,[14] cold and ultracold collisions,[16] and ultracold photoassociation spectroscopy.[17] The laser used in transition frequency measurement will introduce ac-Stark shift, which is unavoidable, by changing the dynamic polarizability.[9–13]

For a given state of an atom or ion, denoted as d, with angular momentum and angular momentum projections denoted as j and m, an electromagnetic field brings a shift in energy as given as[1,4,6–8]

$$\Delta E_{\rm d}(\omega, j, m) = \frac{1}{2}\alpha_{\rm d}(\omega, j, m)E^2, \tag{1}$$

where E is the amplitude of the electric field, which alters with a frequency of ω. The dynamic polarizability becomes static one as the frequency ω becomes zero, which means that the electric field is constant. The dynamic polarizability can be expressed as[1,4,6–8]

$$\begin{aligned}\alpha_{\rm d}(\omega, j, m) &= \alpha_{\rm d}^{\rm S}(j, m) + A\cos\theta_k \frac{m}{j_n}\alpha_{\rm d}^{\rm V}(\omega, j, m) \\ &\quad + \left(\frac{3\cos^2\theta_p - 1}{2}\right)\frac{3m^2 - j(j+1)}{j(2j-1)}\alpha_{\rm d}^{\rm T}(\omega, j, m),\end{aligned} \tag{2}$$

where $\alpha_{\rm d}^{\rm S}$, $\alpha_{\rm d}^{\rm V}$, and $\alpha_{\rm d}^{\rm T}$ are the scalar, vector, and tensor components of the dynamic polarizability respectively, and θ_p is the angle between the polarization direction of the linearly-polarized laser and the z axis. The parameter A changes with light polarization: if the light is linearly polarized, A is zero; if the light is right (left)-handed circularly polarized, A equals $1(-1)$. That is to say, linearly polarized light leads to no vector polarizability and the dynamic polarizability consists of the scalar and tensor components only. In the theoretical calculation, physicists give the average polarizability of those states with the same values of j and $|m|$. That is to say, polarizabilities of those states have the same j and $|m|$ but different signs in m cannot be different.[7,8] This paper will show us the difference in polarizability between the states which have the same value of j and $|m|$ but different signs of m experimentally by measuring the frequency shifts respectively.

We have measured the frequency shifts of the $3D_{5/2,m=|1/2|} \rightarrow 4S_{1/2,m=|1/2|}$ transitions at the magic wavelength[7,8,18,19] of this transition couple in $^{40}Ca^{+}$. The average of these two shifts stays at the constant value of zero but each single shift changes periodically with the angle between polarization direction of the linearly-polarized laser and the z axis. This means that the magic wavelength is "magic" to just the average frequency shift of those two transitions and

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not "magic" to each single one. The frequency shifts of these two transitions can reach the same value of zero at a certain polarized angle of the laser light. In magic wavelength measurement, if we set the laser's polarized angle at this value, it will take us less time to reach the same precision than in Ref. [18].

It is not specific for magic wavelength that the frequency shift changes with the polarized angle of the light periodically. If we change the wavelength of the laser light, the average frequency shift will also stay constant but not at zero and each single shift will change periodically in the constant center. In the transition frequency measurement, the ac-Stark shift is unavoidable for the use of several laser beams. Research on the relationship between frequency shift and laser polarization direction will improve the precision of the transition frequency measurement.

2. Experimental setup

A partial level scheme of $^{40}Ca^{+}$ is depicted in Fig. 1, showing the relevant energy levels and transitions. Because of the magnetic field, each level splits into several Zeeman sub-levels marked with magnetic quantum number on the right side. As a result, the clock transition splits into ten Zeeman components. The two components corresponding to $3D_{5/2,m=|1/2|}$ are sketched in solid lines, of which the frequency shifts are measured under the effect of the laser field at the magic wavelength corresponding to the $3D_{5/2,m=|1/2|} \rightarrow 4S_{1/2,m=|1/2|}$ transition.

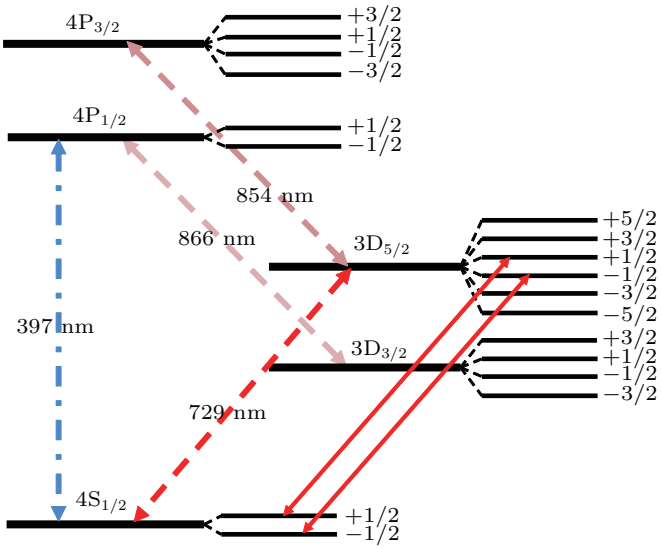


Fig. 1. (color online) Relevant energy levels and transitions of $^{40}Ca^{+}$. Because of the Zeeman effect, all levels split into several Zeeman sub-levels. The 397-nm laser is the cooling laser. The 866-nm laser is used for repumping the ion scattered into $3D_{3/2}$ state back to $4P_{1/2}$ for continuous cooling. The 854-nm light is used for quenching ion in $3D_{5/2}$ state to ground state. The 729-nm transition is the optical clock transition and with magnetic field applied, the clock transition splits into ten Zeeman components.

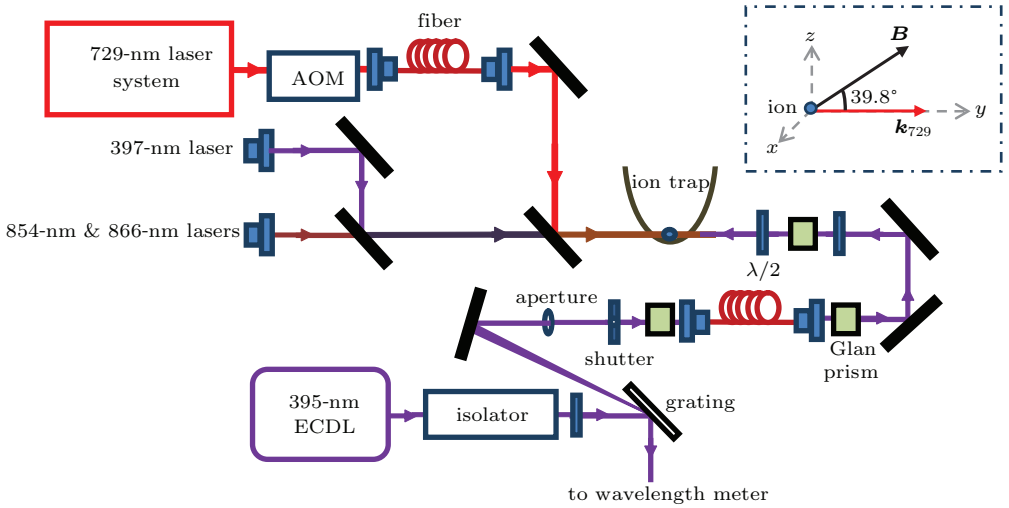


Fig. 2. (color online) Schematic diagram of experimental system. AOM: acousto–optic modulator, $\lambda/2$: 1/2 wave plate, ECDL: external-cavity diode laser. Light from 395-nm diode laser is diffracted by grating. Zero-order diffraction component is guided into the wavelength meter and the first-order one is for the experiment.

The experimental setup is briefly sketched in Fig. 2. At the top right corner, the direction of magnet is indicated clearly, which is in the vertical plane and has an angle of 39.8° with respect to a wave vector of 729-nm laser. The 395-nm laser part is a little different from that in our former work as reported in Ref. [19]. The first-order component of the 395-nm laser diffracted by a grating is selected for the experiment and leads to the trap in the opposite direction of 729-nm laser. The shutter (SRS, SR475) after the grating is used for switching the light on and off. The Glan prisms located in front of and behind the fiber are used for diminishing the power variation of the laser. A half-wave plate is used in front of the ion trap to change the laser polarization direction. None of the probe laser (729 nm), cooling laser (397 nm), repumping laser (866 nm), and quenching laser (854 nm) are depicted in detail, and their descriptions can be found in our previous work.[9,22,23] The line-width of 729-nm laser is measured to be less than 1 Hz and the stability is measured to be less than 2×10^{-15} at 1–

30 s. The 397- and 866-nm lasers are frequency stabilized with transfer cavities,[24] taking the probe laser (729 nm) as reference and the long-term drift is reduced to within 10 MHz for 4 h. The 395-nm laser runs freely and the frequency drift is within 100 MHz for 4 h. Power variation of the laser is reduced to less than 4% for 5 h, monitored by the power meter PM100USB from Thorlabs.

3. Experimental procedure

A single $^{40}Ca^{+}$ ion is trapped in a miniature Paul trap and Doppler cooled with the 397-nm cooling laser and the 866-nm repumping laser. The excess micromotion of the ion is reduced by optimizing the voltages applied to the compensating electrodes. The ion temperature is minimized to a few mK and the ion can be trapped for several days. The pulse sequence used in our experiment is similar to the one used in our clock frequency measurement.[9,22,23] In the cooling process, the 854-nm laser is switched on for 1 ms as shown in Fig. 3 to guarantee that the ion is in the ground state. After 3 ms, the counter is triggered on to record the photon counts. Then the probe light (729 nm) compensated for by an acousto-optic modulator (AOM) is switched on to pump the ion into the $3D_{5/2}$ state and frequency of the AOM is recorded by the computer. The counter starts once again after 4 ms. If the counts are as few as background counts, the ion is pumped into the metastable state successfully. That is to say, a quantum jump happens. The sequence is repeated 30 times and if quantum jumps happen, the probe laser is locked to the clock transition successfully. The magic wavelength about 395 nm is applied together with 729-nm laser subsequently. The time sequence with 395-nm light is carried out 30 times to lock the probe light to the clock transition too. The difference between frequencies with and without the 395-nm laser gives us the frequency shift caused by the 395-nm laser. The time sequence runs with or without the 395-nm laser for about 20 min respectively; about 50 values of frequency shift are recorded in each polarization direction of the 395-nm laser. The half wave plate is rotated 360° in steps of 5° during the measurement.

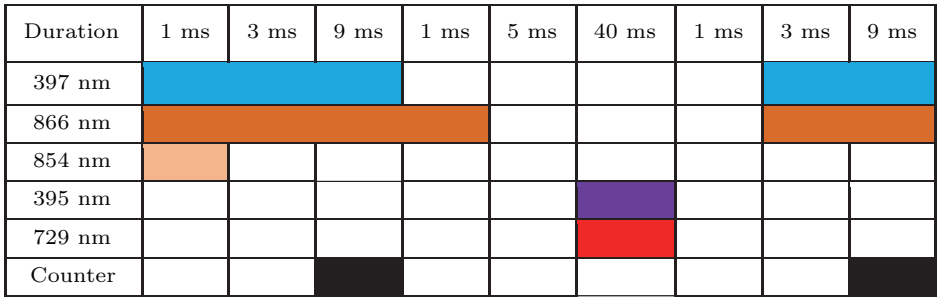


Fig. 3. (color online) Simplified sequence for our experiment. We lock our probe laser to two of the Zeeman components of clock transition with and without 395-nm laser, the frequency difference gives the frequency shift from 395-nm laser, corresponding to $4S_{1/2,m=-1/2} \rightarrow 3D_{5/2,m=-1/2}$ and $4S_{1/2,m=+1/2} \rightarrow 3D_{5/2,m=+1/2}$ transitions.

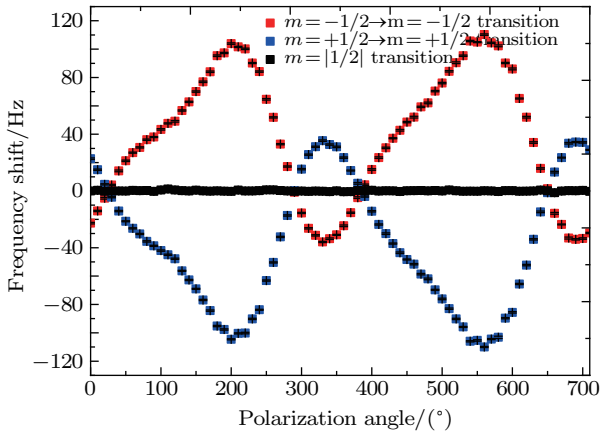


Fig. 4. (color online) Relationships between frequency shift and polarization angle of 395-nm light for different cases. Each point is averaged over 50 measurements. The red point gives the frequency shift of $4S_{1/2,m=-1/2} \rightarrow 3D_{5/2,m=-1/2}$ transition and the blue one shows the frequency shift of $4S_{1/2,m=+1/2} \rightarrow 3D_{5/2,m=+1/2}$ transition. Both the red and the blue points go periodically and they have the opposite values at each angle. The black dot refers to averaged values of red and blue ones. Only statistics error is considered here, which is no more than 0.8 and cannot be drawn obviously.

Under the effect of magic wavelength light, the average of frequency shifts of $4S_{1/2,m=-1/2} \rightarrow 3D_{5/2,m=-1/2}$ and $4S_{1/2,m=+1/2} \rightarrow 3D_{5/2,m=+1/2}$ transition stay at the constant value of zero as shown in Fig. 4. While, the frequency shifts of a single transition ($4S_{1/2,m=-1/2} \rightarrow 3D_{5/2,m=-1/2}$ or $4S_{1/2,m=+1/2} \rightarrow 3D_{5/2,m=+1/2}$ transition) change with the polarized angle of the 395-nm laser periodically and have values opposite to each other.

4. Conclusions and outlook

We measure the frequency shifts of a couple of clock transitions corresponding to $3D_{5/2,m=\pm 1/2}$ with different laser polarizations directions at the magic wavelength of the $4S_{1/2,m=|1/2|} \rightarrow 3D_{5/2,m=|1/2|}$ transition couple. Frequency shifts change with laser polarization periodically and have opposite values constantly. Rotating the polarizer to a certain angle precisely which is about 12.5° or 145° here, both of the shifts go to zero. If the polarizer is fixed at the angles, "four point locking scheme"[25,26] can be replaced with "two point

locking scheme" in magic wavelength measurement, which will take less time to achieve the same accuracy.

In the transition frequency measurement, the lasers used in probing will cause ac-Stark shifts. The average shift of a transition coupled with the same values of angular momentum j and absolute value of angular momentum projection m is constant but not zero. Each single shift corresponding to either of the transition couples will change in a periodical manner with laser polarization direction in the constant center. If the relationship between shift and laser direction is measured specifically, then a certain direction can be chosen to lead to the smallest ac-Stark shift during single transition frequency measurement.

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