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Magic Wavelength of an Optical Clock Transition of Barium *

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Similar to most of the other alkaline earth elements, barium atoms can be candidates for optical clocks, thus the magic wavelength for an optical lattice is important for the clock transition. We calculate the magic wavelength of a possible clock transition between $6s^2\,{}^1S_0$ and $6s5d\,{}^3D_2$ states of barium atoms. Our theoretical result shows that there are three magic wavelengths 615.9 nm, 641.2 nm and 678.8 nm for a linearly polarized optical lattice laser for barium.

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Optical clocks based on neutral atoms have attracted great attention due to their variable applications. Possible applications include next-generation frequency standards, new tests of fundamental physics, more accurate measurements of fundamental constants and their time dependence, and further improvement in global positioning systems.[1−4] Optical lattice traps formed by a far off-resonant laser are very useful for confining cold atoms. Collision shift and broadening of atoms confined in optical lattices can be effectively eliminated. In addition, when atoms are confined to a Lamb–Dicke region, the first-order Doppler shift will vanish.[5,6]

For high precision frequency standards, light shift of the clock transitions caused by a trapping laser needs to be avoided. Thus the wavelength of the trapping light should be tuned to a region where the light shifts of two states of the clock transition cancel each other. This special wavelength is called the magic wavelength. Katori *et al.*[7−9] have proposed to utilize optical lattice traps formed with a magic wavelength trapping laser, and this ingenious technique can greatly improve the established high-accuracy optical frequency standard based on neutral atoms. Optical lattice clocks of alkaline-earth atom Sr and rare-earth atom Yb have been widely studied and have achieved great success in recent years.[10−13] Alkaline-earth metal Ba has a very sharp optical transition $6s^2\,{}^1S_0$–$6s5d\,{}^3D_2$ with a lifetime of about 69 s[14] of the upper level. The natural linewidth of this clock transition is about 2 mHz, thus Ba can also be a good candidate for an optical frequency standard. The cooling and trapping of barium atoms has been realized and reported in Ref. [15], which makes it possible for us to build an accurate optical clock based on barium atoms trapped in an optical lattice. In this Letter, we propose to use the Ba $6s^2\,{}^1S_0$–$6s5d\,{}^3D_2$ transition as a clock transition and present a calculation of magic wavelength for this clock.

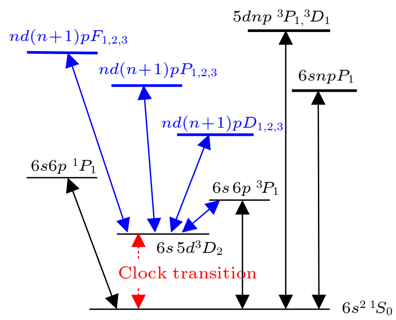

Fig. 1. Diagram of the energy levels for barium atoms and some possible laser couplings.

Calculation of energy shift caused by the trapping laser has been reported before.[16−19] According to second-order perturbation theory, when atoms are in state $|i\rangle$ with energy E_i and Zeeman sublevel m_i, emerged in a trapping laser field with frequency $v = \omega/2\pi$, polarization p, and intensity I, the energy shift of the atomic state, $U_i(\omega, p, m_i)$, can be expressed as

$$U_i(\omega, p, m_i) = -\frac{\alpha_i(\omega, p, m_i) I}{2\varepsilon_0 c}, \tag{1}$$

where $\alpha_i(\omega, p, m_i)$ is the induced polarizability, which can be calculated by summation over the contributions coming from all dipole transitions from the desired level i to all other levels k with the respective Einstein coefficients A_{ki} (spontaneous emission rate for $E_k > E_i$), Zeeman sublevels m' and transition fre-

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quencies $v_{ik} = \omega_{ik}/2\pi$,

$$\alpha_i = 6\pi c^3 \varepsilon_0 \sum_{k,m'} \frac{A_{ki}(2J_k+1)}{\omega_{ik}^2(\omega_{ik}^2-\omega^2)} \begin{pmatrix} J_i & 1 & J_k \\ m_i & p & -m' \end{pmatrix}^2 . \quad (2)$$

The expression in large parentheses denotes a $3J$ symbol. If we know ω_{ik} and A_{ki} in Eq. (2), we can obtain the polarizability α_i.

For barium atoms, the energy diagram can be simplified, as shown in Fig. 1. Here, ${}^1S_0$ is the ground state and ${}^3D_2$ is the metastable triplet state with a lifetime of about 69 s.

Table 1 shows the wave numbers (WN) and probabilities (Einstein coefficients A_{ki}) of transitions originating from the $6s^2\,{}^1S_0$ and $6s5d\,{}^3D_2$ states of barium. We choose the available experimental values as much as possible from Refs. [20,21], then we take part of the theoretical data from Ref. [22], and for the rest we mainly use the values in Ref. [23].

Table 1. Atom transition data of barium.

Lower state $\|i\rangle$	Upper state $\|k\rangle$	WN (cm^{-1})	A_{ki} ($10^6 s^{-1}$)	References
$6s5d\,{}^3D_2$ ($9215.501\,cm^{-1}$)	$6s7p\,{}^1P_1$	32547.033	0.38	[22]
	$6s7p\,{}^3P_2$	30987.240	2.1	[22]
	$6s7p\,{}^3P_1$	30815.512	8.6	[22]
	$5d6p\,{}^1P_1$	28554.221	0.090	[21]
	$5d6p\,{}^1F_3$	26 816.266	0.34	[22]
	$5d6p\,{}^3P_2$	25956.519	16.2	[21]
	$5d6p\,{}^3P_1$	25704.110	56.0	[20]
	$5d6p\,{}^3D_3$	24979.834	11.6	[21]
	$5d6p\,{}^3D_2$	24531.513	33.0	[20]
	$5d6p\,{}^3D_1$	24192.033	18.9	[20]
	$5d6p\,{}^1D_2$	23074.387	0.065	[21]
	$5d6p\,{}^3F_3$	22947.423	32.0	[20]
	$5d6p\,{}^3F_2$	22064.645	7.6	[20]
	$6s6p\,{}^1P_1$	18060.261	0.11	[20]
	$6s6p\,{}^3P_2$	13514.745	0.1	[22]
	$6s6p\,{}^3P_1$	12636.623	0.32	[23]
$6s^2\,{}^1S_0$ (ground state)	$6s18p\,{}^1P_1$	41494.39	0.086	[20]
	$6s17p\,{}^1P_1$	41411.04	0.15	[20]
	$6s16p\,{}^1P_1$	41307.88	0.23	[20]
	$6s15p\,{}^1P_1$	41183.60	0.56	[20]
	$5d8p\,{}^3P_1$	41097.20	0.72	[20]
	$6s14p\,{}^1P_1$	40991.23	0.14	[20]
	$5d8p\,{}^3D_1$	40893.76	0.45	[20]
	$6s13p\,{}^1P_1$	40765.23	0.081	[20]
	$6s12p\,{}^1P_1$	40428.68	0.46	[20]
	$6s11p\,{}^1P_1$	39982.14	1.5	[20]
	$6s10p\,{}^1P_1$	39311.95	0.041	[20]
	$5d7p\,{}^1P_1$	38499.86		[20]
	$6s9p\,{}^1P_1$	37775.28	1.1	[20]
	$5d7p\,{}^3P_1$	36989.98		[20]
	$5d7p\,{}^3D_1$	36495.732		[20]
	$6s8p\,{}^1P_1$	35892.465		[20]
	$6s7p\,{}^1P_1$	32547.033	42.0	[20]
	$6s7p\,{}^3P_1$	30815.512	0.013	[20,22]
	$5d6p\,{}^1P_1$	28554.221	35.0	[20]
	$5d6p\,{}^3P_1$	25704.110	1.1	[20]
	$5d6p\,{}^3D_1$	24192.033	1.5	[20]
	$6s6p\,{}^1P_1$	18060.261	119	[20]
	$6s6p\,{}^3P_1$	12636.623	0.299	[23]

We now calculate the light shift for $m = 0$ levels of the optical clock transition from $6s^2\,{}^1S_0$ to $6s5d\,{}^3D_2$ of a boson barium isotope with nuclear spin of $I = 0$. The magic wavelength is the wavelength of the trapping laser where the light shifts of the two states for a corresponding transition are the same. For the $6s^2\,{}^1S_0$–$6s5d\,{}^3D_2$ clock transition of barium atoms considered in this work, the magic wavelength value corresponds to the crossing of the light shift curves for the $6s^2\,{}^1S_0$ and $6s5d\,{}^3D_2$ states.

Figure 2 displays the dependence of energy level shift difference for barium on wavelength of a linearly polarized trapping laser. The light shift is defined as U/h (U is the energy shift of a state), and the intensity of the trapping laser is 1×10^4 W/cm^2. As shown by the arrows in Fig. 2, at 615.9 nm, 641.2 nm, and 678.8 nm the states $^1S_0$ and $^3D_2$ have the same light shifts. Thus these wavelengths are magic wavelengths for the Ba clock.

We also consider the magic wavelength caused by a circularly polarized laser. The light shifts caused by linearly polarized and circularly polarized lasers with wavelengths around 615 nm, 640 nm and 680 nm are presented in Figs. 3(a), 3(b) and 3(c), respectively. The vertical axis ΔU is defined as $\Delta U = U_{^3D_2} - U_{^1S_0}$, which shows the light shift difference of the two energy levels. The magic wavelength occurs at a point where $\Delta U = 0$. It is found that the new magic wavelengths are 609.3 nm, 636.6 nm and 679.8 nm in the case of a circularly polarized laser field. From Fig. 3(c) we can see that the light shifts caused by linearly and circularly polarized lasers around 680 nm are much closer than other wavelengths.

Now we consider a one-dimensional optical lattice consisting of a partially polarized laser, assuming that the circularly polarized laser intensity is 1/3 of the total laser intensity. The total light shift caused by this trapping laser is the sum of 2/3 of the shift of a linearly polarized laser and 1/3 of the shift of a circularly polarized laser. Then the magic wavelengths of 615.9 nm, 641.2 nm and 678.8 nm should be moved to 613.8 nm, 638.8 nm and 679.0 nm, respectively, according to the polarization of the perturbing laser. Other portions of circularly polarized laser light in one-dimensional or two-dimensional optical lattices can be calculated in the same way and we give some modification to the magic wavelengths.

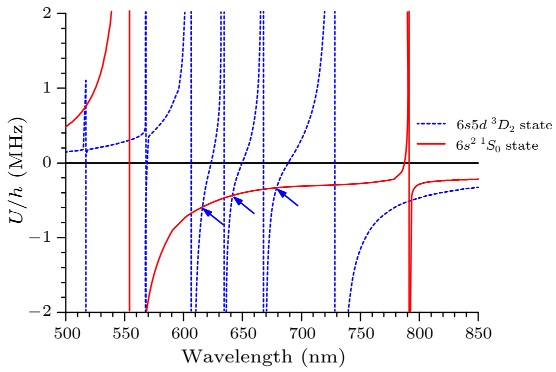

Fig. 2. Dependence of energy level shifts of barium atoms in the ground and $6s5d\,^3D_2\,(m=0)$ states on a linearly polarized trapping laser wavelength. The arrows show the magic wavelength points.

We can also estimate the trap depth of the optical lattice and the slope of the light shift with a linearly polarized laser. The trap depth of the optical lattice at a magic wavelength with a laser intensity of 10^4 W/cm^2 is defined as the maximum temperature of the trapped atoms $T = U/k_B$ (k_B is Boltzmann's constant). The slope of light shift difference at a magic wavelength defined as $k = \frac{d}{d\lambda}(\Delta U)$ ($\Delta U = U_{^3D_2} - U_{^1S_0}$) shows how fast the difference changes with the laser wavelength. These are listed in Table 2.

Table 2. Trap depth and light shift slope at different magic wavelengths.

λ_{magic} (nm)	Trap depth (μK)	K (MHz/nm)
615.9	29.1	0.11
641.2	22.1	0.09
678.8	16.8	0.05

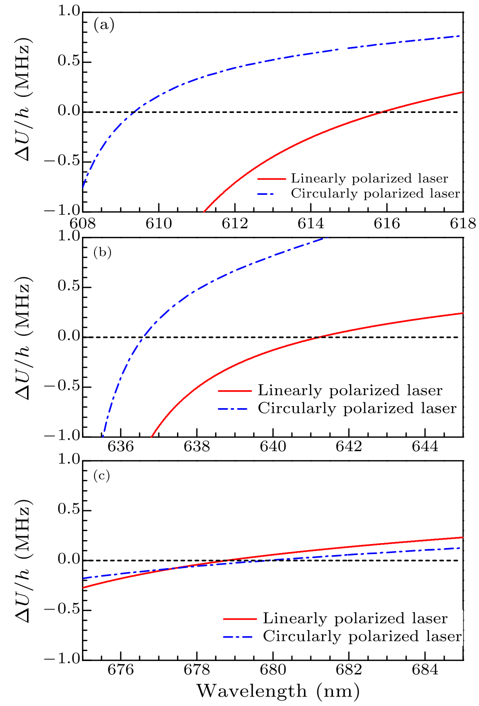

Fig. 3. Difference in light shifts caused by linearly polarized and circularly polarized lasers around (a) 615 nm, (b) 640 nm and (c) 680 nm. The new magic wavelengths occur at 609.3 nm, 636.6 nm and 679.8 nm for a circularly polarized laser field, compared with the previous magic wavelengths of 615.9 nm, 641.2 nm and 678.8 nm, respectively, for a linearly polarized laser. In the calculation, the laser intensity of 1×10^4 W/cm^2 is used.

Based on the calculation and the availability of current commercial lasers, we recommend 678.8 nm as the laser wavelength for optical trapping, because the influence due to possible circularly polarized light is minimal in comparison to the other two wavelengths, 615.9 nm and 641.2 nm. The shift slope is also smaller and the trap depth is deep enough to trap barium atoms.

In summary, we have calculated the magic wavelength for $6s^2\,^1S_0$ to $6s5d\,^3D_2$ clock transition ($m=0$) of boson isotope barium with $I=0$, and we have analyzed and compared the magic wavelengths caused by linearly polarized and circularly polarized lasers. We recommend 678.8 nm as a magic wavelength for an optical lattice laser. This result is helpful for building an optical clock with barium in an optical lattice.

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