Magnetic-sublevel-independent magic wavelengths: Application to Rb and Cs atoms

Sukhjit Singh, B. K. Sahoo, and Bindiya Arora

1Department of Physics, Guru Nanak Dev University, Amritsar, Punjab-143005, India
2Theoretical Physics Division, Physical Research Laboratory, Navrangpura, Ahmedabad-380009, India

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A generic scheme to trap atoms at the magic wavelengths $\lambda_{\text{magic}}$ that are independent of vector and tensor components of the interactions of the atoms with the external electric field is presented. The $\lambda_{\text{magic}}$ for the laser cooling $D_2$ lines in the Rb and Cs atoms are demonstrated and their corresponding polarizability values without vector and tensor contributions are given. Consequently, these $\lambda_{\text{magic}}$ are independent of magnetic sublevels and hyperfine levels of the atomic states involved in the transition, thus, they can offer unique approaches to carrying out many high-precision measurements with minimal systematics. Inevitably, the proposed technique can also be used for electronic or hyperfine transitions in other atomic systems.

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I. INTRODUCTION

Techniques to cool and trap atoms using laser light have revolutionized modern experimental procedures. They are applied not only to carry out very high precision spectroscopy measurements, but also to probe many subtle signatures like parity violation [1], Lorentz symmetry invariance [2], and quantum phase transitions [3]. Vogl and Weitz demonstrated the cooling of Rb atoms by resonating the trap laser light with their $D$ lines [4], while Monroe et al. observed the clock transition in Cs by cooling the atom using the $D_2$ line [5]. As demonstrated in Ref. [6], trapping atoms at $\lambda_{\text{magic}}$ is the foremost process today in a number of applications such as constructing optical lattice clocks. Following this, a number of experimental and theoretical studies have been reported $\lambda_{\text{magic}}$ for Sr atoms to reduce the systematics in the measurements. Using $\lambda_{\text{magic}}$ for trapping and controlling atoms inside high-$Q$ cavities in the strong coupling regime with minimum decoherence for the $D_2$ line of Cs atom has been demonstrated by McKeever et al. [18]. Liu and co-workers experimentally demonstrated the existence of $\lambda_{\text{magic}}$ for the $^{40}\text{Ca}^+$ clock transitions [19].

A linearly polarized light is predominantly used to trap atoms, which is free from the contribution of the vector component of the interaction between atomic states and electric fields. A substantial drawback of these $\lambda_{\text{magic}}$ is that they are magnetic-sublevel dependent for the transitions involving states with angular momenta greater than 1/2. It has also been argued that considering circularly polarized light for trapping could be advantageous due to the dominant role played by the vector polarizability in the ac-Stark shift [9,20]. This may help in augmenting the number of $\lambda_{\text{magic}}$ in some cases but at the same time requires magnetic-sublevel selective trapping. The dependence of magic wavelengths on magnetic sublevels demands the need for state selective traps. To circumvent this problem, it is imperative to find $\lambda_{\text{magic}}$ that are independent of magnetic sublevels.

In this paper, we propose a scheme to trap atoms and ions at the $\lambda_{\text{magic}}$ that are independent of the atomic magnetic and hyperfine levels. They can be used in a number of the applications discussed above. Just for demonstration purposes, we present here $\lambda_{\text{magic}}$ of the widely used $D_2$ transitions of the Rb and Cs atoms. They are useful for optical communications where lasers are tuned to their $D$ lines to trap and repump the atoms in order to prevent them from accumulating in the ground state [21]. Moreover, $D_2$ lines of Rb and Cs are used for studying their microwave spectroscopy [4,5,22,23] and quantum logic gates [24], and to assert the accuracy of the fine structure constant [25]. In this proposal, we only presume that the atomic systems are trapped in sufficiently strong magnetic fields.

II. THEORY

The ac-Stark shift for any state with angular momentum $K$ of an atom placed in an oscillating electric field $\vec{E} = \frac{1}{2} \vec{E} e^{-\text{int}} + \text{c.c.}$ with polarization vector $\hat{e}$ is given as [26]

$$\Delta E_K = -\frac{1}{2} \alpha_{K}(\omega) \hat{e}^2,$$

where $\alpha_{K}(\omega)$ is the total dynamic polarizability for the state $K$ with its magnetic projection $M$ as

$$\alpha_{K}(\omega) = \alpha_{K}^{(0)}(\omega) + \beta(\epsilon) \frac{M}{2K} \alpha_{K}^{(1)}(\omega) + \gamma(\epsilon) \frac{3M^2 - K(K + 1)}{K(2K - 1)} \alpha_{K}^{(2)}(\omega),$$

where $\alpha_{K}^{(i)}(\omega)$ with $i = 0,1,2$ are the scalar, vector, and tensor components of the frequency-dependent polarizability respectively. In the above expression $K$ and $M$ can be replaced suitably by either the atomic angular momentum $J$ or hyperfine angular momentum $F$ with their corresponding magnetic projection $M_J$ or $M_F$, depending upon the consideration of atomic or hyperfine states, respectively. The $\beta(\epsilon)$ and $\gamma(\epsilon)$ are defined as [27]

$$\beta(\epsilon) = i(\hat{\epsilon} \times \hat{\epsilon}^*) \cdot \hat{e}_B,$$

$$\gamma(\epsilon) = (\hat{\epsilon} \times \hat{\epsilon}^*) \cdot \hat{e}_B.$$