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Light shifts induced by nuclear spin-dependent parity-nonconserving interactions in ultracold Fr for the detection of the nuclear anapole moment

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We investigate light shifts induced due to the nuclear spin-dependent (NSD) parity-nonconserving (PNC) interactions for the $^7S_{1/2} - {}^6D_{5/2}$ transition in ultracold ^{210}Fr. We find that for this transition the magnetic sublevels of $F = 13/2$, $M = 9/2$ and $F = 13/2$, $M = 7/2$ shift by the same amount in the same direction due to the E2 transition and by different amounts in opposite directions due to the NSD PNC transition. This situation is favourable for measuring the nuclear anapole moment. For the above mentioned transition, the frequency difference of the $F = 13/2$, $M = 1/2$ to $F = 13/2$, $M = -1/2$ and the $F = 13/2$, $M = 9/2$ to $F = 13/2$, $M = 7/2$ transitions has no first order Zeeman shift and a small second order Zeeman shift. Measuring this frequency difference enables us to obtain information on the nuclear anapole moment, and it is insensitive to magnetic field fluctuation.© Anita Publications. All rights reserved.

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1 Introduction

The two sources of parity nonconservation (PNC) in atomic systems are the neutral current weak (NCW) interactions due to the exchange of the Z boson between the nucleus and the electrons, and the nuclear anapole moment [1]. The NCW interactions can give rise to nuclear spin independent (NSI) as well as nuclear spin dependent (NSD) parity nonconservation, while the interaction of the nuclear anapole moment with the electrons results in parity nonconservation only of the NSD kind [2]. NSI PNC is a probe of new physics beyond the Standard Model [3] and NSD PNC from the nuclear anapole moment provides important information about PNC in nuclei [2]. In heavy atomic systems, the dominant contribution to NSD PNC comes from the nuclear anapole moment. This peculiar moment which corresponds to currents flowing on the surface of a toroid could also exist in other physical situations. Recently the observation of such moments has been reported in metamaterials [4]. The only system for which a non-zero value of NSD-PNC has been reported so far is atomic Cs on which the experiment was performed using the Stark mixing technique

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[5]. However, there are discrepancies between the values of the nucleon-nucleon PNC coupling constants obtained from Cs and nuclear scattering experiments [6]. Therefore, other atomic experiments to observe the nuclear anapole moment are desirable to resolve this controversy.

Several research groups are trying to develop new experiments to search for the nuclear anapole moment using atoms and ions. Nuclear spin independent (NSI) PNC has been detected in atomic Yb using the technique of Stark mixing [7], and this system could also be useful for studying the nuclear anapole moment. Another experiment to observe this parity violating nuclear moment has been proposed based on hyperfine transitions in Fr [8]. If the existence of the nuclear anapole moment is proved using several isotopes of atoms or ions, it would be possible to investigate the dependence of this moment on isotopes [9].

Recently, we had proposed a method for the measurement of light shift induced by the NSD PNC effect using ultracold Fr [10], inspired by a proposal to measure NSI PNC in a single trapped and laser cooled Ba^+ ion by Fortson [11] and elaborated in a subsequent work [12]. In this paper, we report precise calculations of the light shifts induced by the NSD PNC interaction between all the hyperfine sub-levels of the $7S_{1/2}$ and $6D_{5/2}$ transition of the ^{210}Fr isotope. The advantage of considering the $7S_{1/2}$ and $6D_{5/2}$ transition is that it will not have first order contribution from the NSI PNC interaction, which are the dominant contributions in the S-S or S-$D_{3/2}$ transitions. Each level shift is dependent on the angular factors of E2 and PNC E1 matrix elements. We found that combination of transition of $M = 9/2$ and 7/2 states with $M = 1/2$ and $-1/2$ is insensitive to magnetic fluctuations, and gives a large light shift induced by the NSD PNC interaction between the nucleus and the electrons. Our measurement scheme may be useful to study experimentally the NSD PNC effect in ^{210}Fr at the CYRIC, Tohoku University in the near future [13]. In the following sections, we explain the theoretical treatment of the light shift induced by the nuclear anapole moment, following which we discuss the results of our calculations and the proposal for a new measurement scheme.

2 Light shift induced by nuclear anapole moment

We discuss the light shift induced by the nuclear anapole moment. The Hamiltonian due to the NSD PNC interaction is given by [10]

$$H_{PNC}^{NSD} = \frac{G_F}{\sqrt{2}} K_w \boldsymbol{\alpha}\cdot\boldsymbol{I}\, \rho_{nuc}(r) \tag{1}$$

where G_F is the Fermi constant, ρ_{nuc} is the nuclear density, and $\boldsymbol{\alpha}$ is the Dirac matrix. The dimensionless quantity K_w is related to the nuclear anapole moment. The $E1_{\text{PNC}}$ amplitude due to the NSD interaction between the hyperfine states F and F', using Eq (1) for Fr atoms, is given in Ref. [10]. The F and F' are the total angular momenta of the atom in the ground and excited states of the transition, respectively. The PNC transition dipole moment $E1_{\text{PNC}}$ for the two levels in the atom allows us to excite this transition.

The light field is given by

$$E(r,t) = \frac{1}{2}\left[E(r)\, e^{-i\omega t} + c.c.\right], \tag{2}$$

where ω is the laser frequency.

The Rabi frequencies of the PNC and E2 couplings are described as,

$$\Omega_{MM'}^{PNC} = -\frac{1}{2\hbar} \sum\nolimits_i (E1_{MM'}^{PNC})_i\, E_i\,(0), \tag{3}$$

$$\Omega_{MM'}^{E2} = -\frac{1}{2\hbar} \sum\nolimits_{i,j} (E2_{MM'})_{ij} \left[\frac{\partial \mathrm{E}_i(r)}{\partial x_j}\right]_0, \tag{4}$$

where $E1_{MM'}^{PNC}$ and $E2_{MM'}$ are the PNC induced electric dipole transition matrix element and electric quadrupole transition matrix element with M and M' corresponding to the azimuthal quantum numbers of the respective final and initial states of a transition. Following Ref [11], it will be assumed that the Rabi frequency is much larger than the detuning frequency. Thus, the light shifts caused due to the PNC induced E1 transition and the E2 transition are given by

$$\Delta\omega_M^{PNC} \approx -\frac{Re\Sigma_{M'}\left(\Omega_{MM'}^{PNC} * \Omega_{MM'}^{E2}\right)}{\sqrt{\Sigma_{M'}|\Omega_{MM'}^{E2}|^2}} \tag{5}$$

$$\Delta\omega_M^{E2} \approx \frac{(\omega_0 - \omega)}{2} - \sqrt{\Sigma_{M'}|\Omega_{MM'}^{E2}|^2} \tag{6}$$

where ω_0 is the resonant frequency without the laser field. This approximation is used if the laser frequency is close to the resonance.

We consider the transitions between $7S_{1/2}$ and $6D_{5/2}$ of ^{210}Fr, which involve E2, and E1 PNC, NSD amplitudes. The advantage of utilizing this transition as mentioned above is the absence of any contribution from an NSI PNC amplitude. Figure 1 shows the energy diagram and the related transitions. The wavelength of the $7S_{1/2}$ to $6D_{5/2}$ transition is 609 nm. The arrows indicate the transition of F = 13/2 to F' =13/2 and F =11/2 to F' = 11/2, which give two of the largest light shifts induced by NSD PNC in Ref. [10].

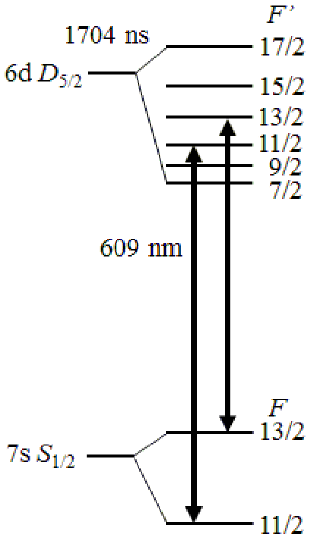

Fig 1.Schematic energy level diagram of ^{210}Fr. Arrows indicate the laser-induced transitions for observing the E2 light shifts and PNC induced light shift.

The selection rule for the E2 transition pertaining to M is $\Delta M = 0, \pm 1, \pm 2$,where $\Delta M' = M' - M$, is the difference of the magnetic quantum number of the hyperfine levels in the transition. One of the selection rules for the PNC E1 transition is $\Delta M = 0, \pm 1$. In Ref. [10], we considered only a situation where $\Delta M = \pm 1$ using a suitable polarization and ***k*** vector of the laser used for excitation, and only states with $M = -1/2$, and 1/2. In this paper, we calculated the light shift for $\Delta M = 0, \pm 1$ for all the magnetic sublevels.

3 Results and Discussion

The reduced matrix elements of the $E1_{MM}^{PNC}$ amplitudes are given in Ref [10]. Using these amplitudes, we calculated the light shift induced by E2, and E1 NSD PNC, for all the magnetic sublevels for the $7S_{1/2}$, $F = 13/2$ to $6D_{5/2}$, $F' = 13/2$ and $7S_{1/2}$, $F = 11/2$ to $6D_{5/2}$, $F' = 11/2$, transitions as shown in Table 1.

Table 1. Estimated light shifts in the hyperfine levels of the $7s\ ^2S_{1/2}\ (F) \rightarrow 6d\ ^2D_{5/2}\ (F')$ transition of ^{210}Fr due to the E2 (in MHz) and NSD PNC (in mHz) interactions with the applied electric field 2×10^6 V/m. Here we have used KW ≈ 0.568 and E2 amplitude as 39.33 ea_0^2

Transition	M	$\Delta\omega_M^{E2}/2\pi$	$\Delta\omega_M^{PNC}/2\pi$
$F = \frac{13}{2} \rightarrow F' = \frac{13}{2}$	1/2	1.70	24.22
	3/2	3.70	31.95
$\Delta M = \pm 1$	5/2	5.70	31.59
	7/2	7.30	29.56
	9/2	8.23	26.23
	11/2	8.01	21.18
	13/2	5.30	12.6
$F = \frac{13}{2} \rightarrow F' = \frac{13}{2}$	1/2	5.88	-2.41
	3/2	5.15	-7.41
$\Delta M = 0$	5/2	3.68	-12.36
	7/2	1.47	-17.3
	9/2	1.47	22.24
	11/2	5.15	27.19
	13/2	9.56	32.13
$F = \frac{11}{2} \rightarrow F' = \frac{11}{2}$	1/2	2.32	–24.09
	3/2	5.00	–31.57
$\Delta M = \pm 1$	5/2	7.54	–30.65
	7/2	9.29	–27.63
	9/2	9.55	–22.53
	11/2	6.49	–13.5
$F = \frac{11}{2} \rightarrow F' = \frac{11}{2}$	1/2	6.85	2.88
	3/2	5.67	8.64
$\Delta M = 0$	5/2	3.33	14.39
	7/2	0.2	–20.15
	9/2	4.89	–25.91
	11/2	10.76	–31.67

First, we consider the case of $\Delta M = \pm 1$. We assume that the E2 laser beam propagates along the z direction with the polarization vector in the x direction to maximize the transition amplitude for $\Delta M = \pm 1$. This case does not allow $\Delta M = 0, \pm 2$. The electric field amplitude E of the E2 laser beam is 2×10^6 V/m, and the E2 amplitude is 39.33 ea_0^2 [10], where a_0 is the Bohr radius. If we use the $F = 13/2$ to $F' = 13/2$ transition with $\Delta M = \pm1$, the E2 light shifts for both M =1/2 and M = –1/2 states are 1.70 MHz, and the NSD PNC induced light shift of M =1/2 (M = –1/2) state is 24.22 (–24.22) mHz. Therefore, measuring the RF frequency of the transition between M = 1/2 and M = –1/2 states give twice the PNC induced light shift and the cancelation of the E2 light shift, i.e. the fluctuation of the E2 light shift due to its laser intensity fluctuation is also canceled. The magnetic field of 1 G, which is applied to fix the quantization axis as the z direction, results in a first order Zeeman shift of 0.215 MHz for M = 1/2 state with a g-factor of 2/13 for F =13/2. In this case, it is necessary to suppress the Zeeman-shift fluctuation determined by the fluctuation of the magnetic field. This light shift requires a magnetic-field fluctuation of less than 1.3×10^{-7} G. The residual magnetic field also should be less than 10^{-7} G. This requirement is extremely challenging.

Next, we consider the case of $\Delta M = 0$. We assume that the E2 laser beam propagates in a direction which corresponds to tilting the z axis by an angle of 45 degrees in the direction of the x axis. The selection rule $\Delta M = 0$ is maximized and a smaller $\Delta M = \pm 2$ amplitude also exists. The selection rule of $\Delta M = \pm 1$ is not allowed. The maximum E2 Rabi frequency for $|\Delta M| = 2$ is 3.562 MHz. To avoid the $\Delta M = \pm 2$ transition, we have to apply a magnetic field larger than 13.34 G, which corresponds to a first order Zeeman shift of 7.124 MHz with a g-factor for $6D_{5/2}$ state of 62/325 in order to separate the $\Delta M = 2$ states. This Zeeman shift between $|\Delta M| = 2$ states is double the largest E2 ($|\Delta M| = 2$) Rabi frequency, which is equivalent to an interaction time width. This width is half of the first period in the Rabi oscillation of the E2 ($|\Delta M| = 2$) transition. Therefore, $\Delta M = \pm 2$ transitions can be ignored if the magnetic field is larger than 13.34 G.

In particular, the E2 light shifts for $F = 13/2$, $M = 7/2$ and 9/2 states with $\Delta M = 0$ also have the same values of 1.47 MHz, as shown in Table 1. This coincidence is due to the same value of the Wigner 3J factors for the E2 transition $F = 13/2$, $M = 7/2$ and 9/2 with q = 0 for both states. Moreover, the signs of the NSD PNC induced light shifts in $F = 13/2$, $M = 7/2$ and 9/2 states are opposite. Therefore, a pair consisting of M = 7/2 and 9/2 is favourable for measuring NSD PNC effect because of the cancelation of the E2 light shift.

We define the shift of frequency as $\Delta\omega_{\mathrm{M}} \equiv \Delta\omega_{\mathrm{M}}^{\mathrm{E2}} + \Delta\omega_{\mathrm{M}}^{\mathrm{PNC}} + E_{\mathrm{Zeeman}}$ for the transition between $7S_{1/2}$, F =13/2, M and $6D_{5/2}$, F' =13/2, M' with $\Delta M = 0$, where E_{Zeeman} is the Zeeman shift. The frequency difference between two different magnetic sublevels in the hyperfine ground state of F =13/2 is defined as $\delta\omega_{\mathrm{M1,\,M2}} \equiv \delta\omega_{\mathrm{M1}} - \delta\omega_{\mathrm{M2}}$. The frequency difference of M = 1/2 and –1/2 is written as $\delta\omega_{1/2,\,-1/2}$. Likewise, that of M = 9/2 and 7/2 is written as $\delta\omega_{9/2,\,7/2}$.

The difference of NSD PNC induced shift $\Delta\omega^{\mathrm{PNC}}/2\pi$ for $\Delta\omega_{1/2,\,-1/2}$ is –4.82 mHz, and that for $\delta\omega_{9/2,\,7/2}$ is 39.54 mHz from Table 1. Subtracting the frequency difference of $\delta\omega_{9/2,\,7/2}$ from $\Delta\omega_{1/2,\,-1/2}$ results in the cancelation of the first order Zeeman shift, as shown in Fig 2 (b), and the reduction of second order Zeeman shift because both the signs of the curves representing the Zeeman shifts as a function of magnetic field for these transitions are positive. Using the Breit-Rabi formula [14], the Zeeman shift of each magnetic sublevels in $7S_{1/2}$, $F = 13/2$ and $F = 11/2$ is given by

$$\hbar\Delta\omega^{B} = -\frac{(h\Delta v)}{2(2I+1)} - g^{J}\mu_{B}BM \pm \frac{(h\Delta v)}{2}\sqrt{1+\frac{4M}{2I+1}\,x+x^{2}} \tag{7}$$

$$x \equiv (g_{J}+g_{I})\,\frac{\mu_{B}B}{h\Delta v} \tag{8}$$

where $\Delta v \equiv A\,(I + 1/2)$ is the hyperfine splitting between $7S_{1/2}$, $F = 13/2$ and $F = 11/2$, the hyperfine coupling constant in $7S_{1/2}$ state for ^{210}Fr is 7 195.1 MHz [15], the nuclear spin for ^{210}Fr is 6, the Landég-factor g_J is 2, the g-factor of nuclear spin g_I for ^{210}Fr is 0.0003913 [16], the μ_B is the Bohr magneton, and the B is the magnitude of magnetic field. The sign of plus (minus) in Eq (7) corresponds to the state $F = I + 1/2 = 13/2$ (F

$= I - 1/2 = 11/2$).

The difference of $\delta\omega_{1/2,\,-1/2}$ and $\delta\omega_{9/2,\,7/2}$ is written as

$$\delta\omega = \delta\omega_{1/2,\,-1/2} - \delta\omega_{9/2,\,7/2} = -\,44.5\ (\mathrm{NSD}) + 1414\,0700\ (\mathrm{Zeeman@13.34\ G}) + 21\ (\delta B/0.1334\mathrm{mG})\mathrm{mHz} \qquad (9)$$

where the difference of Zeeman shift ~ 1.414 is given by Eqs (7) and (8), and δB is the fluctuation of magnetic field. Therefore, if the magnitude of magnetic field is stabilized to less than 10^{-5}, NSD PNC induced light shifts can be detected. It requires that the currents of coils generating the bias field of 13.34 G should be stabilized to less than 10^{-5}, and the earth magnetic field of 0.3 G should be suppressed by 1/2250 using magnetic shields. The experiment in these conditions is feasible using currently available technology. Furthermore, the NSD PNC induced light shift via $D_{5/2}$ state for Ba^+ ion is 0.009 mHz, and that for Ra^+ ion is 0.11 mHz [17]. Therefore, 44.5 mHz, the PNC induced light shift for the $7S_{1/2}$ to $6D_{5/2}$ transition in $^{210}\mathrm{Fr}$ is the largest value in the literature.

In order to account for only the NSD light shift in the measurement, we suggest the following experimental procedure, as shown in Fig 2. (i) We prepare the magneto-optical trapping for Fr. The trapped atoms are loaded into the 3D optical lattice. (ii) The atoms are spin polarized in the $7S_{1/2}$, $F = 13/2$, $M = 13/2$ state by applying a bias magnetic field and laser beam resonant for the $7S_{1/2}$, $F = 13/2$ and $7P_{3/2}$, $F'' = 13/2$ transition with σ^+ polarization, and repumping beam with $\sigma^\pm$ polarization because $M = 13/2$ state is a dark state in this configuration. (iii) The atoms are irradiated with the E2 laser beam with a wavelength of 609 nm. Figure 2(a) shows the energy diagram of magnetic sublevels with the E2 light shifts. For simplicity, Zeeman shifts are not shown. Raman lasers with two frequencies are irradiated to atoms to perform the stimulated Raman adiabaticpassage (STIRAP) in three-levels [18] from $M = 13/2$ state to $M = 9/2$ state. (iv) The four laser beams are applied to perform the STIRAP in five levels [19] in order to create a superposition state of $M = 9/2$ and 1/2. (v) The RF fields resonant with $M = 9/2$ and 7/2, and with $M = 1/2$ and $-1/2$ transitions are applied, as shown in Fig 2 (b). The resonance frequencies of these RF transitions include the PNC induced light shifts. As the interaction time width is 1/1704 ns = 587 kHz, which is larger than the difference of $\delta\omega_{1/2,\,-1/2}$ and $\delta\omega_{9/2,\,7/2}$, RF field with a single frequency can excite these two transitions simultaneously. (vi) Then, we use the state selective detection techniques for $M = 7/2$ and $M = -1/2$, as follows. After the interaction time of 1704 ns, which is the natural lifetime of the $6D_{5/2}$ state, the microwave (MW) field with a frequency of 46.8 GHz transfers the population in the state $F = 13/2$, $M = 7/2$ to $F = 11/2$, $M = 7/2$. The other MW field transfers that in the state of $F = 13/2$, $M = -1/2$ to $F = 11/2$, $M = -1/2$. Then, the "blaster" beam, which is resonant with the transition between $7S_{1/2}$, $F = 13/2$ and $7P_{3/2}$, $F'' = 15/2$, is applied to blow about the atoms remaining in $F = 13/2$ by radiation pressure. (vii) The MW field resonant with only $F = 11/2$, $M = -1/2$ state to $F = 13/2$, $M = -1/2$ is applied. The trapping beam near resonance with the transition between $7S_{1/2}$, $F = 13/2$ and $7P_{3/2}$, $F'' = 15/2$ (frequency of 718 nm) is applied and the fluorescence of atoms during this interaction is detected by the photo multiplier tube (PMT). This data gives $\delta\omega_{1/2,\,-1/2}$. (viii) Next, the blaster beam is applied again. Then, the MW field resonant with only $F = 11/2$, $M = 7/2$ state to $F = 13/2$, $M = 7/2$ is applied. Likewise, the atoms in $M = 7/2$ state is detected. From this, $\delta\omega_{9/2,\,7/2}$ is obtained. Substituting $\delta\omega_{1/2,\,-1/2}$ and $\delta\omega_{9/2,\,7/2}$ into Eq (7), the frequency difference $\delta\omega$ is obtained as in Eq (9).

Repeating the measurement through the procedure from (i) to (viii) for different magnetic fields and fitting the difference of Eq (7) to the data, we obtain the theoretical curve as a function of B as shown in Fig 3. From Eq (9), the signature of the NSD PNC induced light shift is the negative value of – 44.5 mHz at $B = 0$. Although we cannot directly measure the $\delta\omega$ at $B = 0$ using this method, the fitting function at $B = 0$ indicates the negative value due to the NSD PNC induced light shift. Thus, the NSD PNC induced light shift is obtained as $\delta\omega$ intercept at $B = 0$.

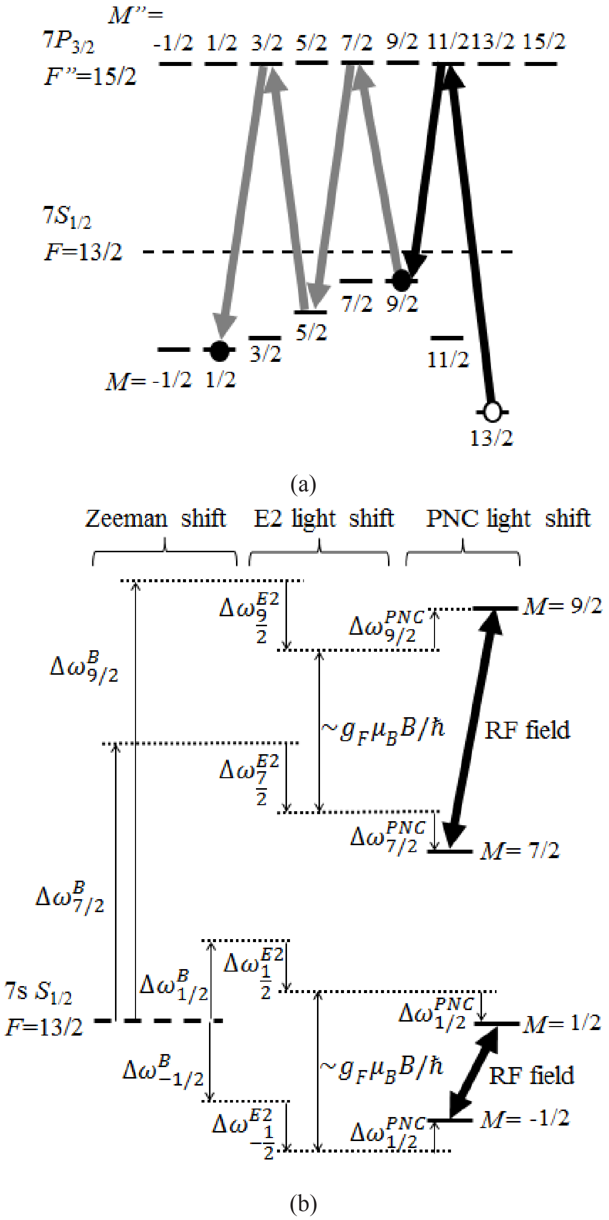

Fig 2. (a) Energy diagram and Raman transitions to prepare the atom in $M = 9/2$ and 1/2 state before applying the RF field. The opened and filled circles represent the initial and final states of atoms for Raman processes, respectively. The dashed line is the energy level in $F = 13/2$ state without E2 light shift. The solid lines are energy levels of magnetic sublevel with E2 light shifts. The Zeeman shifts also exist but are not shown. The black arrows indicate STIRAP from $M = 13/2$ to $M = 9/2$ via $7P_{3/2}$, $F'' = 15/2$ state as an intermediate state. The grey arrows also indicate other STIRAP to create a superposition state of $M = 9/2$ and $M = 1/2$. (b) Magnetic sublevels (shown only for $M = 9/2$, 7/2 and $M = \pm 1/2$) of the $F = 13/2$ level of the $7S_{1/2}$ state with the corresponding RF transitions. The E2 light shifts are $\Delta\omega^{\mathrm{E2}}_{9/2} = \Delta\omega^{\mathrm{E2}}_{7/2}$ and $\Delta\omega^{\mathrm{E2}}_{1/2} = \Delta\omega^{\mathrm{E2}}_{-1/2}$. Energy differences between $M = 9/2$ and 7/2, and between $M = 1/2$ and $-1/2$ without NSD PNC light shifts have the same 1st order Zeeman shift $g_F \mu_B B/\hbar$.

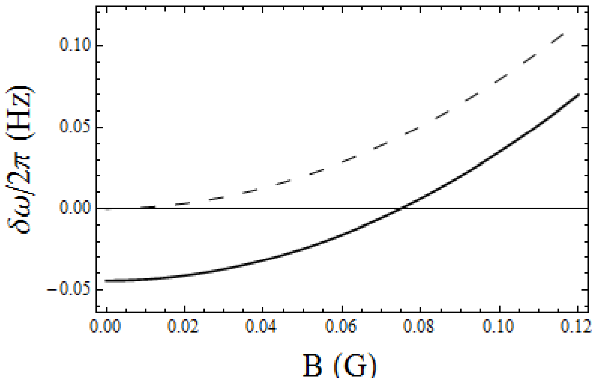

Fig 3. Energy curve as a function of B. The dashed and solid lines represent the frequency differences of $\delta\omega = \delta\omega_{1/2,\,-1/2} - \delta\omega_{9/2,\,7/2}$ without and with NSD PNC induced light shifts, respectively.

4 Conclusion

We calculated the light shift induced by E2 $\Delta\omega_M^{E2}$ and E1 NSD PNC $\Delta\omega_M^{\mathrm{PNC}}$ for ^{210}Fr for all the magnetic sublevels in the $7S_{1/2}$, F =13/2 to $6D_{5/2}$, F = 13/2, and $7S_{1/2}$, F = 11/2 to $6D_{5/2}$, F = 11/2 transitions. We found that the magnetic sublevels of F =13/2, M = 9/2 and F = 13/2, M = 7/2 have the same E2 light shift and opposite NSD PNC light shift, which is suitable for measuring the nuclear anapole moment. We also found that the frequency difference of $\delta\omega_{1/2,\,-1/2}$ and $\delta\omega_{9/2,\,7/2}$ has no first order Zeeman shift and a small second order Zeeman shift. Measuring this frequency difference enables us to obtain the value of K_W in Eq (1), which is related to the PNC nucleon-meson coupling constant [20]. This quantity is insensitive to magnetic field fluctuations. We are planning to perform this experiment at CYRIC, Tohoku University, Japan [21] in the near future. The observation of the NSD PNC light shift using ultracold Fr could provide unambiguous information on the existence of the nuclear anapole moment and resolve the controversy that has arisen from the discrepancy between the results of the Cs nuclear anapole moment and nuclear scattering experiments.

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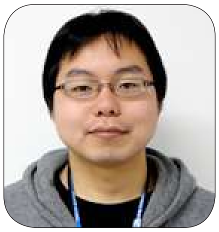

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