PROGRESS TOWARD MEASURING THE $6S_{1/2} \leftrightarrow 5D_{3/2}$ STRONGLY FORBIDDEN MAGNETIC DIPOLE TRANSITION MOMENT IN Ba^+

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INTRODUCTION

- The weak interaction between the nucleons and the electrons in atoms through the exchange of Z_0 Bosons results in parity non conservation (PNC) in atomic system[1,2]. PNC results in the mixing of P states into S states ($S = S + \varepsilon_{PNC} P$), manifesting as a non vanishing electric dipole transition amplitude $E1_{PNC}$ [1,2].
- PNC measurements are a tool for studying electroweak physics at low energy scale, with an opportunity to explore for physics beyond the standard model[3−5].
- Measuring $E1_{PNC}$ is made difficult due to the presence of an unknown magnetic dipole transition moment ($M1$) which ends up being the leading source of systematic error in our parity nonconservation measurement. Hence, we are interested in the precise measurement of $M1$ in Ba^+ for the $6S_{1/2}(m) \leftrightarrow 5D_{3/2}(m')$ transition with a linearly polarized 2051 nm laser.
- To date there are only two theory calculations that have been reported for $M1$ in Ba^+
  $M1 = 80 \times 10^{-5}\mu_B$ [6]
  $M1 = 20 \times 10^{-5}\mu_B$ [7]
- Therefore, the measurement of $M1$ is crucial for the PNC experiment and might be enlightening for atomic many body calculations.

TECHNIQUE

- We propose to measure $M1$ by manipulating the much larger electric quadrupole transition moment ($E2$) and polarization of the 2051 nm laser beam[8].

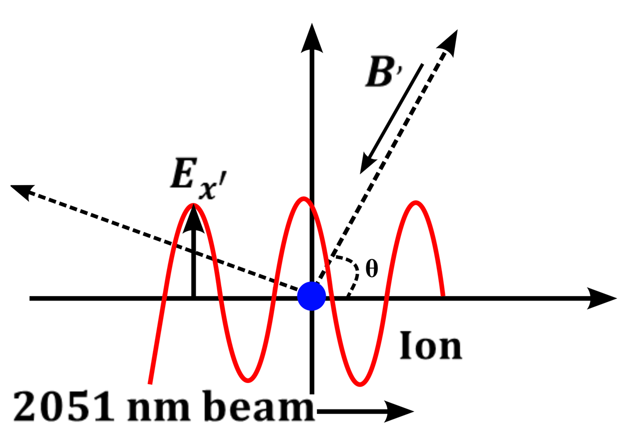


Figure 1: $E_{x'}$ and $B_{y'}$ refer to the field components of the 2051 nm laser beam which lies in the $X'Y'$ plane. The externally applied magnetic field, which lies along the Z axis, defines the quantization axis for the atoms. Y and Y' axes are parallel and out of this page.

- We focus on measuring the Rabi frequency for the transition $6S_{1/2}(m = \mp 1/2) \leftrightarrow 5D_{3/2}(m = \pm 3/2)$ and $6S_{1/2}(m = \mp 1/2) \leftrightarrow 5D_{3/2}(m = \mp 1/2)$ in $^{138}Ba^+$ with a 2051 nm laser beam. The $\Delta m = 0$ transition contains contribution from both $E2$ and $M1$.

The Rabi frequency for the $\Delta m = 0$ transition can be expressed as:

$$\Omega^{(0)} = |\Omega^{(0)}_{E2} + \Omega^{(0)}_{M1}| \quad (1a)$$

$$\Omega^{(0)}_{E2} = \frac{-ik}{4\sqrt{10}\hbar} E2\sin(2\theta) E_{x'} \quad (1b)$$

$$\Omega^{(0)}_{M1} = \frac{1}{\sqrt{6}\hbar} M1\sin(\theta) B_{x'} \quad (1c)$$

TECHNIQUE (CONTD)

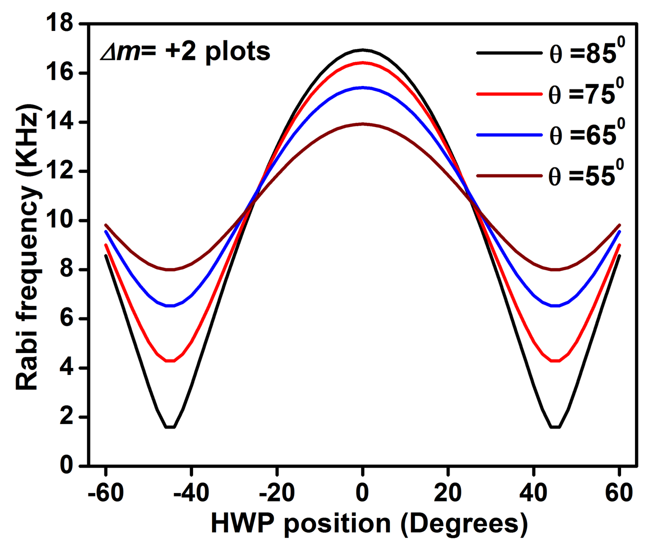
$\Omega^{(0)}_{E2}$ contribution can be cancelled by using circular polarization and...

- Shifting θ symmetrically about $90°$ by a small angle δ $\Rightarrow \Delta\Omega = |\Omega(90° + \delta) - \Omega(90° - \delta)| = 2\Omega^0_{M1}$
- Reversing the sense of circular polarization $\Rightarrow \Delta\Omega = |\Omega^+(90° \pm \delta) - \Omega^-(90° \pm \delta)| = 2\Omega^0_{M1}$
- Varying the state initialization with optical pumping $\Rightarrow \Delta\Omega = |\Omega^\uparrow(90° \pm \delta) - \Omega^\downarrow(90° \pm \delta)| = 2\Omega^0_{M1}$
- To extract $M1$ from Ω^0_{M1}, we need to measure the electric field ($|E|$) at the ion and θ. This can be done with a $|\Delta m| = +2$ transition, driven by a linearly polarized 2051 nm beam.

The Rabi frequency for the $\Delta m = +2$ transition is given by:

$$\Omega^{(2)}_{E2} = \frac{ikE_2}{2\sqrt{30}\hbar}\sin(\theta)[\cos(\theta)E_{x'} - iE_{y'}] \quad (2)$$

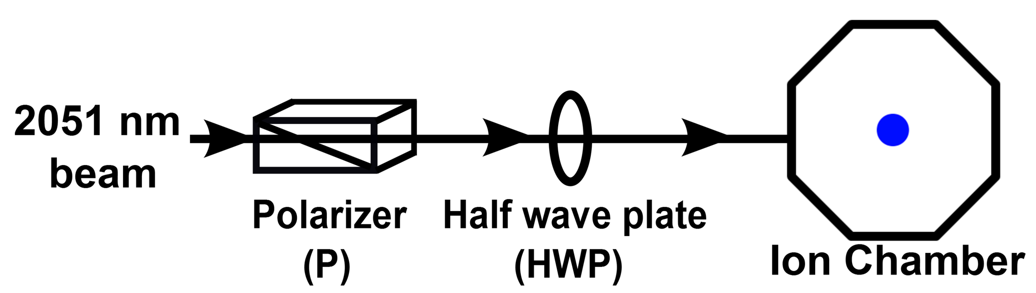
$\Delta m = +2$ curves as a function of the half wave plate (HWP) position for different values of θ is given below:



- The most challenging systematic facing this measurement is the precise control over the 2051 nm beam.
- These systematics can be studied with this type of "linear polarization rotation (PR) measurements".

PR MEASUREMENT PROCEDURE

The schematic of the experimental set up for the polarization rotation measurement is given below:



In this procedure, we the have measured the Rabi frequency for the $6S_{1/2} \leftrightarrow 5D_{3/2}$ transition with $\Delta m = 0$ and $\Delta m = +2$ as a function of the linear polarization angle of the 2051 nm beam. In case of a linearly polarized laser beam, the x and the y components of the electric field vector can be expressed as:

$$E_{x'} = |E|\sin(2\phi) \quad (3a)$$

$$E_{y'} = -|E|\cos(2\phi) \quad (3b)$$

PR MEASUREMENT PROCEDURE (CONTD)

Simplified expression for the Rabi frequency in terms of the HWP optical axis orientation for the $\Delta m = 0$ and $+2$ turns out to be:

$$\Omega^{(0)} = \sqrt{A^2\sin^2(2\phi) + B^2\cos^2(2\phi)} \quad (4a)$$

$$\Omega^{(2)}_{E2} = C\sin(\theta)\sqrt{\cos^2(\theta)\sin^2(2\phi) + \cos^2(2\phi)} \quad (4b)$$

Where, $A = \frac{k|E|}{4\sqrt{10}\hbar}E_2\sin(2\theta)$, $B = \frac{|E|}{\sqrt{6}\hbar c}M_1\sin(\theta)$
and $C = \frac{k|E|E_2}{2\sqrt{30}\hbar}$

This procedure allows us to put an upper bound on $M1$. The expression for $M1$ in terms of the fit parameters turns out to be:

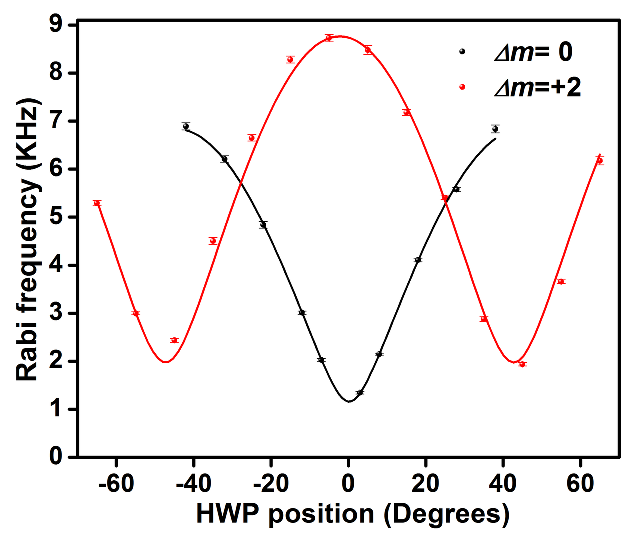
$$M1 = \frac{kc\sqrt{\frac{3}{5}}E2B\cos(\theta)}{2A} \quad (5)$$

RESULTS

In this measurement, we are looking for

1. How high the peak of the $\Delta m = +2$ curve goes, i.e., how much of light is coming out in the linearly polarized mode.
2. The offset in $\Delta m = 0$ curve. This offset depends upon:-
   a) The extinction ratio of the polarizer.
   b) The quality of the HWP.
   c) The stress induced birefringence (SIBR) introduced by the viewports of the ion chamber.
3. Asymmetry in the bottom of the $\Delta m = +2$ curve. This asymmetry arises if the phase retardance (Γ) of the HWP $\neq 180°$ (not a good HWP)

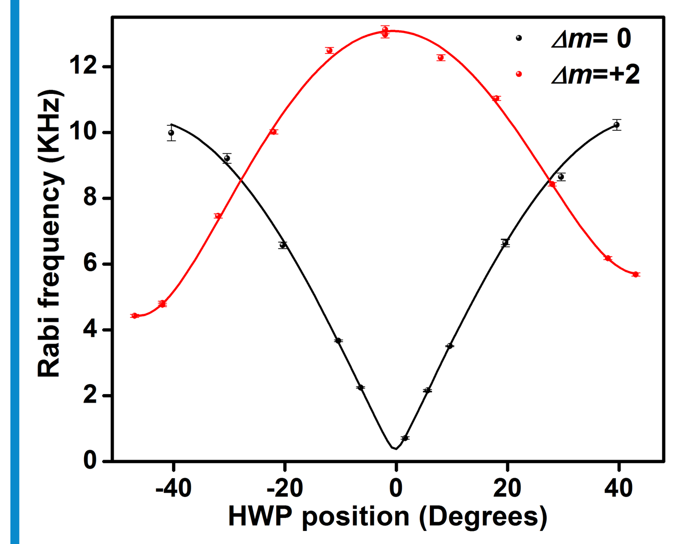
The measured Rabi frequency for $\Delta m = 0$ and $\Delta m = 2$ transition as a function of the linear polarization angle of the 2051 nm beam is given below:



Fit parameters	
A	(6.843 ± 0.039) KHz
B	(1.158 ± 0.036) KHz
C	(8.996 ± 0.148) KHz
θ	$76.996° \pm 0.970°$

- One can clearly see the asymmetry in the $\Delta m = +2$ curve indicating a bad HWP.
- A very high offset is observed here. The extracted $M1$ in this case turns out to be: $M1 \leq 1571.36 \times 10^{-5}\mu_B$
- We upgraded the polarizer with a proper calcite Glan Thompsson (GT) polarizer. The corresponding Rabi frequency that was measured for both these transitions are illustrated in the next column.

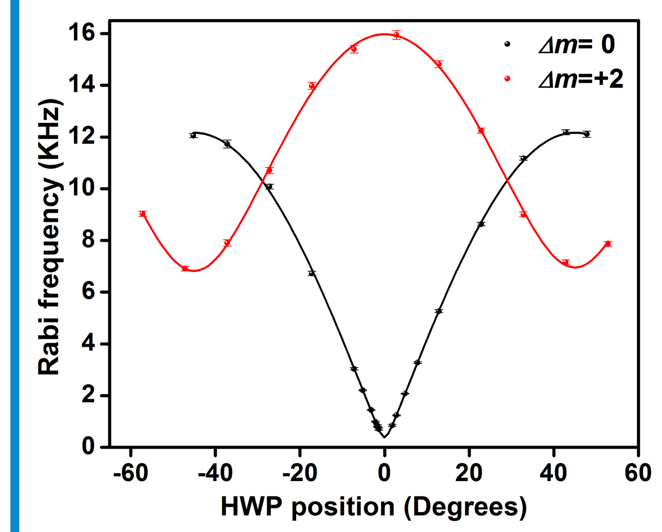
RESULTS (CONTD)



Fit parameters	
A	(10.390 ± 0.052) KHz
B	(0.375 ± 0.097) KHz
C	(14.190 ± 0.069) KHz
θ	$67.179° \pm 0.295°$
Γ	$174.426° \pm 0.501°$

- Again, there seems to be an asymmetry in the polarization scan for Rabi frequency that was measured for the $\Delta m = +2$ transition. This asymmetry arises because the HWP that had been used is quoted to have a phase retardance of $\Gamma = 176.86°$ ($\frac{\lambda}{2.0355}$ plate) at 2051 nm.
- The extracted $M1$ from the fit parameters gets modified as $M1 \leq 329.9 \times 10^{-5}\mu_B$. This HWP was replaced by a new one which was quoted to have a phase retardance of $180°$ ($\lambda/2 \pm \lambda/500$).

The recent measurements with all these changes in place is illustrated below:



Fit parameters	
A	(12.166 ± 0.033) KHz
B	(0.380 ± 0.025) KHz
C	(17.707 ± 0.069) KHz
θ	$64.457° \pm 0.306°$
Γ	$180.474° \pm 0.379°$

- The new HWP with phase retardance $\Gamma = 180.474°$ can be expressed as a $\frac{\lambda}{1.995}$ wave plate.
- The extracted $M1$ in this case turns out to be: $M1 \leq 289.4 \times 10^{-5}\mu_B$.

FUTURE WORK

- Rebuild the trap by replacing the fused silica viewports with the CaF_2 viewports to reduce the SIBR.
- Install the μ metal shield in place to reduce the decoherence time.
- Redo these measurements to check if the offset has gone down.

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