Proposal for Parity Nonconservation Measurements in Single Trapped Ba^+

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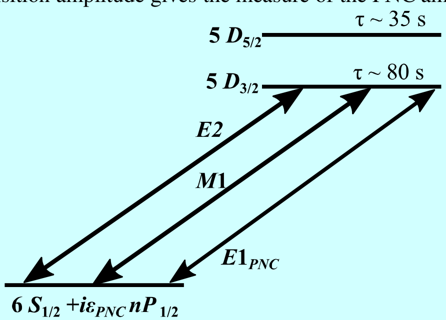
Introduction

- The weak interaction between the nucleons and the electrons in atoms through the exchange of Z_0 Bosons results in parity non conservation (PNC).[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] between S and the D states.
- Interference between $E1_{PNC}$ and an allowed electromagnetic transition amplitude gives the measure of the PNC amplitude.[3]



Motivation

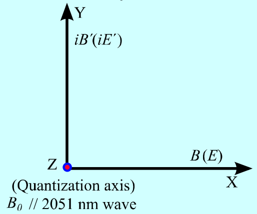
- PNC measurements are a tool for studying electroweak physics at low energy scale, with an opportunity to explore for physics beyond the standard model.[4-6]
- So far, the best PNC measurements have been reported with a beam of cesium atoms with an experimental uncertainty of 0.35%[7]. PNC measurements with trapped ions offer better experimental precision.
- We propose to measure the PNC amplitude in free space using a free running 2051 nm laser instead of a standing wave cavity to avoid the complications involved in this case.

Advantage of using Ba^+ for PNC measurements

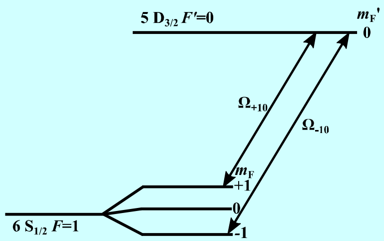
- Precision measurements have been done previously with Ba^+.[8, 9]
- Ba^+ has an electronic structure similar to that of Cs, thus enabling similar sub percent precision in atomic theory calculation.[10]
- For the Ba ion $Z = 56$, relativistic correction factor to the Z^3 scaling for $Z > 50$ is $K(Z,R) = 2.9$[2] with the corresponding enhancement factor of $Z^3 K(Z,R) \approx 510 \times 10^3$.
- Accuracy of a single Ba^+ PNC measurement is predicted to be 0.13%[11]

The updated proposal

- In this updated proposal, we intend to access the transition $6S_{1/2}(F=1) \leftrightarrow 5D_{3/2}(F'=0)$ in an odd isotope of Ba^+($^{137}Ba^+$) with a 2051 nm laser to measure the corresponding parity violating shift. The $E2$ moment is absent in this transition ($F + F' < 2$; $E2$ forbidden) and only $M1$ and $E1_{PNC}$ amplitudes are present.



- The corresponding geometry is shown above
  - External magnetic field (B_0) sets the quantization axis and is directed along the Z axis.
  - 2051 nm laser beam along the quantization axis, i.e., $B_0 \parallel \vec{k}$.
  - Direction of polarization of the laser beam lies in the XY plane
- From the figure shown above, $B_x = B$; $B_y = iB'$; $E_x = -iE'$ and $E_y = E$
- E and E' are in phase with B and B'; $E = B$ and $E' = B'$.



- Defining the ratio of the $E1_{PNC}$ amplitude to the $M1$ amplitude as R, the Rabi frequency associated with the $\Delta m = +1$ and $\Delta m = -1$ transitions are:
  - $\Omega_{+1,0} \approx M1(B + B')(1 + R)$
  - $\Omega_{-1,0} = M1(B - B')(1 - R)$
- On reversing the sense of circular polarization by reversing the external magnetic field ($B \to \tilde{B}$ and $B' \to -\tilde{B}'$) we have:
  - $\tilde{\Omega}_{+1,0} = M1\,(\tilde{B} - \tilde{B}')(1 + R)$
  - $\tilde{\Omega}_{-1,0} = M1\,(\tilde{B} + \tilde{B}')(1 - R)$
  - Let $\Omega^2 = {\Omega_{+1,0}}^2 + {\Omega_{-1,0}}^2$ and $\tilde{\Omega}^2 = {\tilde{\Omega}_{+1,0}}^2 + {\tilde{\Omega}_{-1,0}}^2$
  - $\frac{\Omega^2 - \tilde{\Omega}^2}{\Omega^2 + \tilde{\Omega}^2} = \frac{4BB'}{B^2 + B'^2} \cdot \frac{R}{1 + R^2}$ (1)

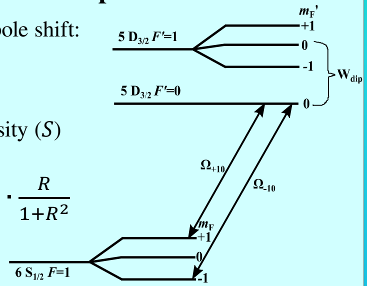
Inclusion of the Dipole shift

- W_{dip} is the off resonant dipole shift:

$$W_{dip} = \frac{|\langle 6P|\vec{r}\cdot\vec{E}|5D\rangle|^2}{W_{5D3/2} - W_{6P}};$$

$$\propto E^2 + E'^2 \approx \text{Intensity } (S)$$

$$\frac{\Omega^2 - \tilde{\Omega}^2}{\Omega^2 + \tilde{\Omega}^2} + \frac{S - \tilde{S}}{S + \tilde{S}} = \frac{4BB'}{B^2 + B'^2} \cdot \frac{R}{1 + R^2}$$



- S can be calibrated by driving the transition $6S_{1/2}(F=2) \leftrightarrow 5D_{3/2}(F'=0)$, where only $E2$ amplitude is present and $E1_{PNC}$ amplitude is relatively smaller so that the RHS of Eq. 1 ≈ 0.

Measurement of the $M1$ amplitude

- To measure the $E1_{PNC}$ amplitude using the above described method, the $M1$ amplitude must be measured precisely.
- The atomic theory calculations predict $M1$ amplitude to be larger than expected due to electron-electron correlation effects. On comparing the magnitudes of interaction strengths of the corresponding transition we have[12-14]: $\langle E1_{PNC}\rangle : \langle M1\rangle : \langle E2\rangle \approx 1 : 10^5 : 10^7$.
- The $M1$ amplitude can be extracted from an $E2 - M1$ interference in $^{138}Ba^+$. This requires the magnetic field orientation and the polarization of the 2051 nm laser fields to be known precisely.
- In this method, the size of $M1$ and $E2$ amplitudes is adjusted by controlling the polarization of the 2051 nm laser beam and the direction of the quantization axis.
- We are currently pursuing the measurement of the $M1$ amplitude.[15]

References

1. *Phys. Lett.* B **48**, 111 (1974)
2. *J. Phys. France*, **35**, 899 (1974)
3. *Phys. Scr.* **T40**, 15 (1992)
4. *Phys. Rev. Lett.* **65**, 2963 (1990)
5. *Phys. Rev. C* **46**, 2587 (1992)
6. *Phys. Rev. D* **53**, 2724 (1996)
7. *Science*, **275**, 1759 (1997)
8. *Phys. Rev. A* **77**, 052503 (2008)
9. *Phys. Rev. A* **85**, 043418 (2012)
10. *Phys. Rev. Lett.* **109**, 203003 (2012)
11. *Phys. Rev. Lett.* **70**, 2383 (1993)
12. *Phys. Rev. A* **75**, 032507 (2007)
13. *Phys. Rev. A* **74**, 062504 (2006).
14. *Phys. Rev. A* **81**, 052506 (2010).
15. Manuscript in preparation.

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