Quantum entanglement of ions for light dark matter detection

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Summary

- Linear ion trap systems can be used as sensors for weak electric fields.

  ⇨ Electric fields induced from light DM (ALP and DP) can be detected.

- The DM signals can be enhanced by using entangled ions.

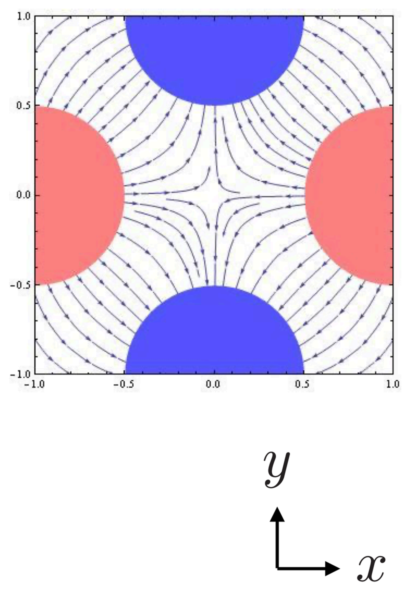
  Eigenstates of DM operators return its eigenvalues and number of ions N appears in amplitude.

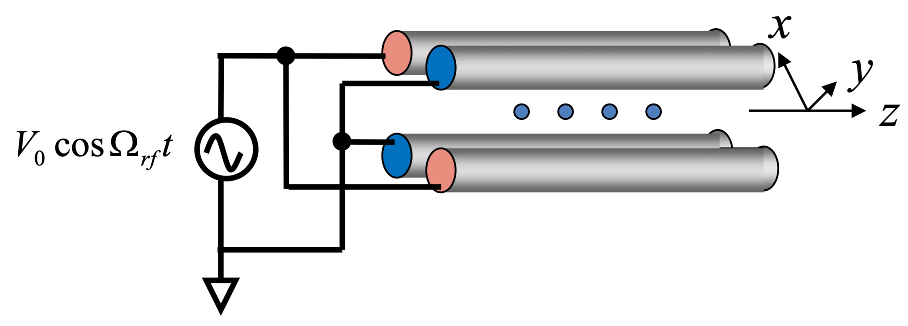
  ⇨ N^2 enhancement for probability rather than N

Paul ion trap and qubits

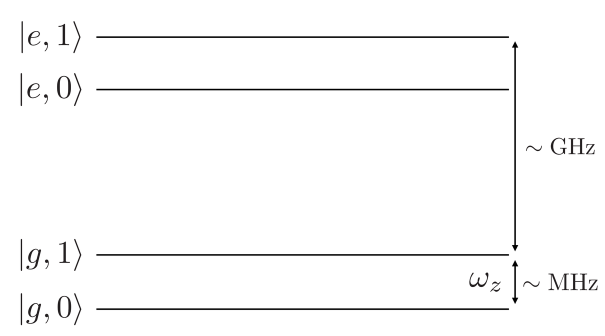
https://www.nii.ac.jp/qis/first-quantum/symposium/2012/pdf/tanaka_summerSchool2012.pdf

- Ions are captured by trap of electric field.
- Ions are aligned at balanced points between the Coulomb and trapped potentials.





- Cooled ion has two-level state of spin, $|g\rangle$ and $|e\rangle$, and two-level collective oscillation state of z-direction, $|0\rangle$ and $|1\rangle$.



ALP/Dark photon DM

- Light ALP/dark photon DM fields are coherently oscillating in their coherent times.

$$a(t) = a_0 \cos(m_a t - \phi_a)\ , \qquad \vec{E}'(t) = \vec{E}'_0 \sin(m_{\rm DP} t - \phi_{\rm DP})$$

- Electric fields from DM are

$$E_{a,z}(t) = \epsilon_a a_0 \sin(m_a t - \phi_a), \quad E_{{\rm DP},z}(t) = \epsilon_{\rm DP} \cos\theta_z \vec{E}'_0 \sin(m_{\rm DP} t - \phi_{\rm DP})$$

J. Ouellet and Z. Bogorad, 1809.10709

$$\epsilon_a \approx \frac{B_z}{2}\frac{g_{a\gamma}}{m_a}(m_a R)^2 \left[\left(\gamma - \frac{1}{2}\right)^2 + \left(\frac{\pi}{2}\right)^2\right]^{1/2}$$

(Assuming cavity for ALP)

$$g_{a\gamma} = 4.4 \times 10^{-11}\ {\rm GeV}^{-1} \times \left(\frac{\dot{\bar{n}}}{0.1\ {\rm s}^{-1}}\right)^{1/4}\left(\frac{T_{\rm total}}{1\ {\rm day}}\right)^{-1/4}\left(\frac{T}{0.4\ {\rm s}}\right)^{-1/2}\left(\frac{R}{3\ {\rm m}}\right)^{-2} \times \left(\frac{B_z}{100\ {\rm mT}}\right)^{-1}\left(\frac{m_{\rm ION}}{37\ {\rm GeV}}\right)^{1/2}\left(\frac{m_a}{10\ {\rm neV}}\right)^{-1/2}\left(\frac{\rho_{\rm DM}}{0.45\ {\rm GeV\ cm^{-3}}}\right)^{-1/2},$$

Single ion case

$$H_X = eE_{X,z} z$$
$$= e\epsilon_X \sin(m_X t - \phi_X)\sqrt{\frac{\rho_{\rm DM}}{m_{\rm ION}\omega_z}}(a^\dagger e^{i\omega_z t} + a e^{-i\omega_z t})$$
$$\equiv 2\alpha_X \sin(m_X t - \phi_X)(a^\dagger e^{i\omega_z t} + a e^{-i\omega_z t})$$

- When $\omega_z = m_X$, electric fields from DM excite the oscillator level coherently. The probability after a coherent time T is

$$P_1(T) \approx \dot{\bar{n}} T + |\alpha_X|^2 T^2 \qquad T = \frac{2\pi}{m_{\rm DM} v_{\rm DM}^2} \sim 0.4\,{\rm s} \times \left(\frac{10\,{\rm neV}}{m_{\rm DM}}\right)$$

Heating noise

- Ion trap has good sensitivity for electric field! (95% C.L.)

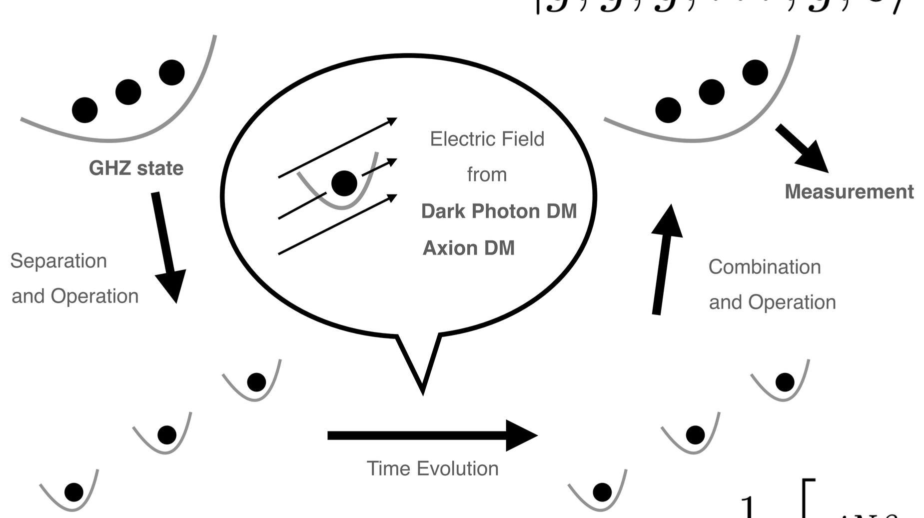
$$E_z = 3.6\ {\rm nV/m} \times \left(\frac{\dot{\bar{n}}}{0.1\ {\rm s}^{-1}}\right)^{1/4}\left(\frac{T_{\rm total}}{1\ {\rm day}}\right)^{-1/4}\left(\frac{T}{0.4\ {\rm s}}\right)^{-1/2}\left(\frac{m_{\rm ION}}{37\ {\rm GeV}}\right)^{1/2}\left(\frac{\omega_z}{10\ {\rm neV}}\right)^{1/2}$$

$$\epsilon = 6.4 \times 10^{-12} \times \left(\frac{\dot{\bar{n}}}{0.1\ {\rm s}^{-1}}\right)^{1/4}\left(\frac{T_{\rm total}}{1\ {\rm day}}\right)^{-1/4}\left(\frac{T}{0.4\ {\rm s}}\right)^{-1/2} \times \left(\frac{m_{\rm ION}}{37\ {\rm GeV}}\right)^{1/2}\left(\frac{m_{\rm DP}}{10\ {\rm neV}}\right)^{1/2}\left(\frac{\rho_{\rm DM}}{0.45\ {\rm GeV\ cm^{-3}}}\right)^{-1/2}$$

Multi-ion case

$$|\Psi_{\rm GHZ}\rangle = \frac{1}{\sqrt{2}}(|g,g,\dots,g,0\rangle + |e,e,\dots,e,0\rangle)$$

$$|g,g,g,\dots,g,0\rangle + iN\beta_{\rm i}\,|e,g,g,\dots,g,0\rangle + \cdots$$



$$\frac{S}{\sqrt{B}} \propto N^{3/2}$$

if noises are not coherent, $B \propto N$.

$$\frac{1}{\sqrt{2}}\left[\left(\frac{|g,0\rangle + |g,1\rangle}{\sqrt{2}}\right)^{\otimes N} + \left(\frac{|g,0\rangle - |g,1\rangle}{\sqrt{2}}\right)^{\otimes N}\right]$$

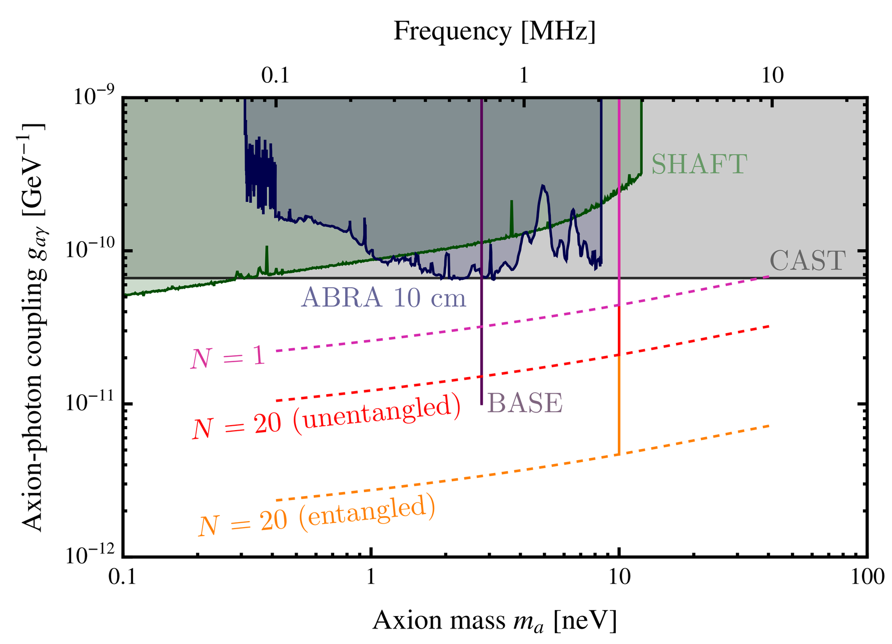
Eigenstate of operator from DM!

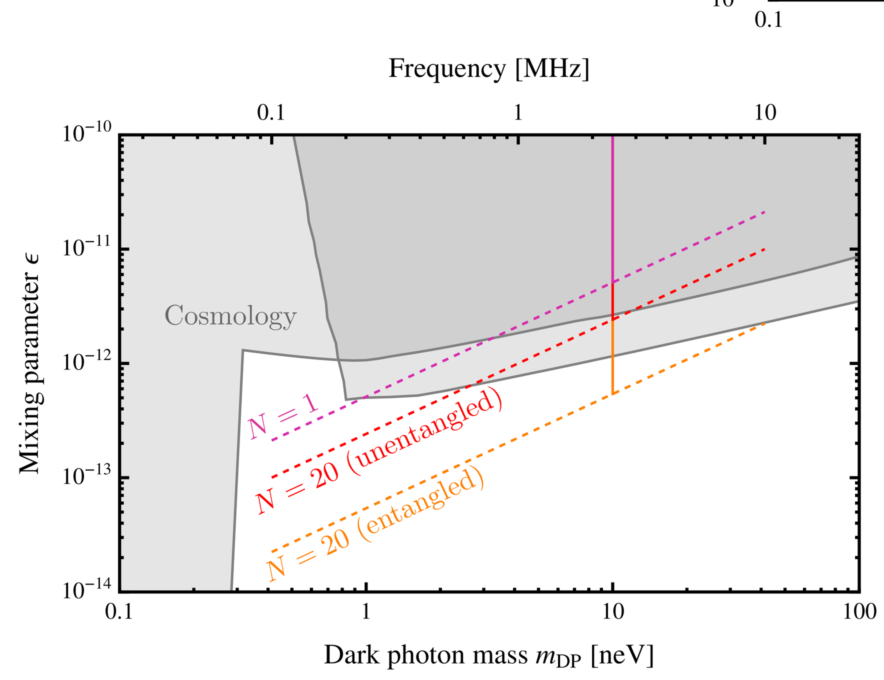
$$\frac{1}{\sqrt{2}}\left[e^{iN\beta_{\rm i}}\left(\frac{|g,0\rangle + |g,1\rangle}{\sqrt{2}} + \beta_{\rm r}\frac{|g,0\rangle - |g,1\rangle}{\sqrt{2}}\right)^{\otimes N} + e^{-iN\beta_{\rm i}}\left(\frac{|g,0\rangle - |g,1\rangle}{\sqrt{2}} + \beta_{\rm r}\frac{|g,0\rangle + |g,1\rangle}{\sqrt{2}}\right)^{\otimes N}\right]$$

$$\overline{\beta_{\rm r}^2} = \overline{\beta_{\rm i}^2} = |\alpha_X|^2 T^2/2$$

Result

- The created coherence effect succeeds to improve the sensitivity.





- The mass is scanned by changing the trap frequencies.
- Only terrestrial constraints are shown for figure of ALP.