Reading Notes on Theses

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The document is organized to make notes on the thesis I have read.

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In this thesis, a lot of detailed techniques are discussed

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III. QUANTUM SIMULATION OF INTERACTING SPIN MODELS WITH TRAPPED IONS

A. Introduction

- Feynman‘s idea could be addressed as a digital quantum simulator, and the Hamiltonian is constructed from piecewise application of local Hamiltonians, Trotter expansion

$$e^{-iHt} \approx \left(e^{-iH_1t/n}e^{-iH_2t/n}e^{-iH_3t/n}\cdots e^{-iH_lt/n}\right)^n \tag{3.1}$$

  Thus, error in simulating Hamiltonian can be kept uder a given value by property choosing the number of steps.

- Analog quantum simulator follows the mathematically equivalent evolution, restricted into a few classes of Hamiltonians.
  - strongly correlated system
  - high temperature superconductors
  - heavy fermion materials
  - quantum Monte Carlo
  - density matrix renormalization group

B. Trap Setup

The trap is a three layer linear Paul trap with 6 DC electrodes and 6 ground electrodes and 2 RF electrodes. The bottom and top layers of electrodes are approximately 250μm and the middle layer of RF electrodes are 125μm

- RF frequency 38.6MHz, and the quality factor is about 200. The input power to the helical resonator is approximately 27dBm(500mW), which may generate a radio-frequency voltage of about $200--300$ volts, leading to secular frequencies of $\omega_x \approx \omega_y \approx 2\pi \times 5$MHz

- $$V_{end} = \frac{V_1+V_2+V_5+V_6}{4}, \quad V_{central} = \frac{V_3+V_4}{2}$$

  And the voltage is generated by High precision HV module from ISEG. The central and end voltages can be changed to manipulate the principla axes of the trap along the transverse directions.

- The Z-push voltage $V_z = \frac{V_1+V_5-V_2-V_6}{2}$ controls the ions position along Z-axis.

- The end difference and central difference are used to minimize the radio frequency micromotion

C. Ion Trapping

Static electric field is impossible to create a 3-D stationary point for charged particle, thus we need to use some radio frequency fields for ion trapping theory with an effective confining potential, which can be demonstrated by only one dimension

$$E(x) = E_0(X)\cos\Omega t \tag{3.2}$$

If the field is homogeneous, then $E_0(X)$ is a constant with varying X, then the charged particle could be described as a dynamic equation

$$m\ddot{X}(t) = F(t) = eE_0(X_0)\cos\Omega t \tag{3.3}$$

The solution can be easily obtained as

$$X(t) = -\frac{eE_0}{m\Omega_{rf}^2}\cos\Omega_{rf}t + X_0 \tag{3.4}$$

Now, we have already known the solution to a homogeneous electric field for charged particles. Furthermore, we can approximate the solution to a electric field with a small inhomogeneity

$$E_0(X) = E_0(X_0) + \frac{\partial E_0(X)}{\partial X}\bigg|_{X=X_0}(X - X_0) \tag{3.5}$$

Where we suppose the displacement is small enough so that we can approximate the solution with above homogeneous electric field.

The force applied on the charged particle can be now rewritten as

$$\begin{aligned} F_X(t) &= e(E_0(X_0) + \frac{\partial E_0(X)}{\partial X}\bigg|_{X=X_0}(X - X_0))\cos\Omega t \\ &= eE_0(X_0)\cos\Omega t + e\frac{\partial E_0(X)}{\partial X}\bigg|_{X=X_0}(X - X_0)\cos\Omega t \\ &= eE_0(X_0)\cos\Omega t - \frac{e^2E_0(X_0)}{m\Omega_{rf}^2}\frac{\partial E_0(X)}{\partial X}\bigg|_{X=X_0}\cos^2\Omega t \end{aligned} \tag{3.6}$$

The time average of this force is

$$\begin{aligned} F_X(t) &= -\frac{e^2E_0(X_0)}{2m\Omega_{rf}^2}\frac{\partial E_0(X)}{\partial X}\bigg|_{X=X_0} \\ &= -e\frac{\partial}{\partial X}\left(\frac{eE_0^2(X_0)}{4m\Omega_{rf}^2}\right)\bigg|_{X=X_0} \end{aligned} \tag{3.7}$$

Thus we can define a effective potential which can be denoted by ponderomotive potential for time averaged confining potential and the ponderomotive is independent of the electric charge sign(negative or positive)

$$\Psi_{\text{pond}}(X) = \frac{eE_0^2(X)}{4m\Omega_{rf}^2} \tag{3.8}$$

In addition, the region of $E_0(X) = 0$ is referred to as a *radio-frequency null*, which can be a point, a collection of discrete points or a line depending on the geometry of the trap. And the static potentials are adjusted so that the micromotion can be minimized, which can avoid the coupling to vibrational modes of the ion chain and resulting in quantum decoherence by heating up the modes.

D. Ion Loading

The photoionization of the neutral Yb is a two-photon ionization which includes the $^1S_)$ level to the $^1P_1$ level, and then $^1P_1$ continuum or more. As a typical setup, 1mW399 laser with beam waist about 100μm and the second step can be performed by any light below 394.1nm. Typically, we can use 369.5nm as a ionizaiton light or 355nm with a typical energy 1mW, but single ions can be loaded one by one with 369.5, however multiple ions will be loaded simutaneously with 355.

The other isotopes will be a dark spot in the $^{171}Yb^+$ ion chain, the isotope shift between the $^{171}Yb^+$ and $^{174}Yb^+$ in the $^1S_0 -^1 P_1$ transition frequency is about 800MHz which is more than the broadened width(200MHz typically) The protection beam which is red detuned from the $^2S_{1/2} \rightarrow^2 P_{1/2}$ resonance by 600MHz, and it is on during the loading.

E. Crystal Recapture

The collisions with background gases(mostly Hydrogen) will cause the melting of ion crystal, the probability will increase with increasing ion chain number. Typically, the collision event will occur per five minutes on an average for a chain of 10 ions. In order to recapture the crystal, Doppler cooling beam and protection beam should be turned on and the trap depth should be lowered by 11dB for its RF power, and the DC depth should be also reduced to a lower level.

F. $^{171}Yb^+$ qubit

$^{171}Yb^+$ is a really nice qubit candidate with magnetically insensitive two-level system , and the nucleus has a spin 1/2 so that there exist a hyperfine structure in the electronic levels. The ground state is $^2S_{1/2}$, and the hyperfine splitting cause it into two states $^2S_{1/2}\left|F=1,m_F=0\right\rangle$, $^2S_{1/2}\left|F=0,m_F=0\right\rangle$, and the $F=1$ states has three manifolds with projection into $m_F=-1, m_F=0, m_F=1$, which can be splitted by a externally applied magnetic field $B_Y \approx 5$G with a zeeman splitting 1.4MHz/G $\times B_Y$, however the hyperfine splitting is a second-order Zeeman splitting which could be denoted by

$$\delta_{zz} = (310.8)B^2\text{Hz}, \quad B \text{ in Gauss} \tag{3.9}$$

and the hyperfine splitting without external magnetic field is 12642.812118466MHz. However, the $^{174}Yb^+$ has no nucleus spin so that there is no hyperfine structure in its electronic levels.