Reading Notes on Theses

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LIST OF FIGURES

LIST OF TABLES

CONTENTS

I. 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

$$e^{-iHt} \approx \left(e^{-iH_1 t/n} e^{-iH_2 t/n} e^{-iH_3 t/n} \cdots e^{-iH_l t/n}\right)^n \tag{1}$$

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

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- 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 $\omega_x \approx \omega_y \approx 2\pi \times 5\text{MHz}$
- $$V_{end} = \frac{V_1 + V_2 + V_5 + V_6}{4}, \quad V_{central} = \frac{V_3 + V_4}{2}$$

  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

$$E(x) = E_0(X)\cos\Omega t \tag{2}$$

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

$$m\ddot{X}(t) = F(t) = eE_0(X_0)\cos\Omega t \tag{3}$$

The solution can be easily obtained as

$$X(t) = -\frac{eE_0}{m\Omega_{rf}^2}\cos\Omega_{rf}t + X_0 \tag{4}$$

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

$$E_0(X) = E_0(X_0) + \frac{\partial E_0(X)}{\partial X}\bigg|_{X=X_0}(X - X_0) \tag{5}$$

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

$$\begin{aligned} F_X(t) &= e(E_0(X_0) + \frac{\partial E_0(X)}{\partial X}\bigg|_{X=X_0}(X - X_0))\cos\Omega t \\ &= eE_0(X_0)\cos\Omega t + e\frac{\partial E_0(X)}{\partial X}\bigg|_{X=X_0}(X - X_0)\cos\Omega t \\ &= eE_0(X_0)\cos\Omega t - \frac{e^2E_0(X_0)}{m\Omega_{rf}^2}\frac{\partial E_0(X)}{\partial X}\bigg|_{X=X_0}\cos^2\Omega t \end{aligned} \tag{6}$$

The time average of this force is

$$\begin{aligned} F_X(t) &= -\frac{e^2E_0(X_0)}{2m\Omega_{rf}^2}\frac{\partial E_0(X)}{\partial X}\bigg|_{X=X_0} \\ &= -e\frac{\partial}{\partial X}\left(\frac{eE_0^2(X_0)}{4m\Omega_{rf}^2}\right)\bigg|_{X=X_0} \end{aligned} \tag{7}$$

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)

$$\Psi_{\text{pond}}(X) = \frac{eE_0^2(X)}{4m\Omega_{rf}^2} \tag{8}$$

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 $^{1}S_0 - ^{1} P_1$ transition frequency is about 800MHz which is more than the broadened width(200MHz typically) The protection beam which is red detuned from the $^{2}S_{1/2} \rightarrow^{2} P_{1/2}$ 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 $^{2}S_{1/2}$, and the hyperfine splitting cause it into two states $^{2}S_{1/2}\left|F=1, m_F=0\right\rangle$, $^{2}S_{1/2}\left|F=0, m_F=0\right\rangle$, 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

$$\delta_{zz} = (310.8)B^2\text{Hz}, \quad B \text{ in Gauss} \tag{9}$$

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.

Doppler cooling can be considered as a momentum kick with different directions which occupy different probabilities, thus there are more atoms absorb photons moving in opposite direction with a red detuned 369.52nm laser beam from resonance about 25MHz, the transition occurs on $^{2}S_{1/2} - -^{2}P_{1/2}$. Furthermore, the Doppler cooling is exerted on the hyperfine states that a sideband is required(1% of the carrier strength) that couples the $^{2}S_{1/2}\left|F=0, m_F=0\right\rangle$ and $^{2}P_{1/2}\left|F=1, m_F=0\right\rangle$, and the frequency difference is 14.74GHz. The optical power in the cooling beam used is approximately 25μW focused to a spot 100μm $\times$ 10μm for about 3ms. Furthermore, a re-pump laser at 935.2nm and the sideband at 3.07GHz is generated by fiber-eom that re-pump $^{2}D_{3/2}$ that $^{2}P_{1/2}$ states leak into with probability of 0.005 upto $^{3}D[3/2]_{1/2}$that will decays back to the cooling cycle $^{2}S_{1/2}$ without mixing the qubit states, because the transition $^{3}D[3/2]_{1/2}\left|F=0, m_F=0\right\rangle \rightarrow^{2} S_{1/2}\left|F=0, m_F=0\right\rangle$ is forbidden. And the laser beam power is about 20mW and is not focused tightly(about hundreds of microns beam waist at the ions), the the laser is frequency stabilized using the software lock(digital PID). Finally, there is also a leak into the 10-year state

$^2F_{7/2}$, then the 638.6nm laser is scanned from 38.6102 to 638.6151 to repump it back to the main cooling cycle, and the event occurs once every couple of hours for s single atom.