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PHYSICAL PRINCIPLES FOR QUANTUM HARDWARE MODELS

Part I

Quantum Optics

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Course Overview

- The idea is to have a series of introductory courses about the main hardware models used for Quantum Computation (QC)

  - Harmonic oscillator quantum computer
  - Optical photon quantum computer
  - Optical cavity quantum electrodynamics
  - Ion traps
  - Nuclear magnetic resonance
  - Superconductivity
  - Etc…

- In the first part, we focus in the following models models

  - Harmonic oscillator quantum computer
  - Optical photon quantum computer
  - Optical cavity quantum electrodynamics

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    - Harmonic oscillator quantum computer
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- We intend to go into the details (physics, math) of these systems

- To this intent some previous (basic) knowledge about Quantum Mechanics, Quantum Optics, and Quantum Electrodynamics are needed

- The first model we will discuss about is the ...

<u>The Simple Harmonic Oscillator</u>

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- The first model we will discuss about is the ...

The Simple Harmonic Oscillator

- It does not serve as a good QC

- However, from a pedagogical point of view it can be used to illustrate the basic concepts of QM

- In a practical point of view it has applications in a variety of problems in modern physics

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- The second model we will discuss is ...

Optical Photon Quantum Computer

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- The second model we will discuss is ...

Optical Photon Quantum Computer

- There are several proposals for quantum devices.
- Perhaps one of the most popular are that based in optical techniques
- Simple devices like mirros and beamspliters can be used for elementary manipulations of photons
- Photons are chargeless particles; they do not interact directly with each other
- The use of non-linear optical material mediates their interaction

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- The third model we will discuss is …

Optical Cavity Quantum Electrodynamics (QED)

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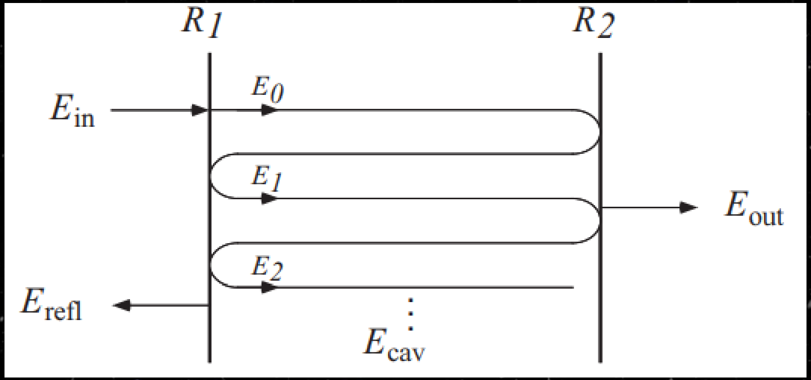
Optical Cavity Quantum Electrodynamics (QED)

- In Cavity QED we access a regime that involves coupling of single atoms to only a few (one or two) optical modes
- Photons in the cavity (Fabry-Perrot) have the opportunity to interact many times with the atoms before escaping



Nielsen-Chuang book

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- The third model we will discuss is …

Optical Cavity Quantum Electrodynamics (QED)

- Quantum Information can be represented by photons states using cavities with atoms to provide interactions between photons

- The idea is that **Photon interact with an atom that interacts with another photon causing na overall interaction between the two photons**

- **This mediator introduces aditional noise**

Quantum information processing machines can be realized in nature?.

Experimental realization of quantum circuits, algorithms and systems are extremely challenging.

In this course we will explore some physical principles related to the implementation of quantum information in real devices cited before.

BASIC QUESTION

Q- What are the experimental requirements for building a quantum computer?

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BASIC QUESTION

Q- What are the experimental requirements for building a quantum computer?

- Qubits - the elementary units of the theory

— To realize a quantum computer, we must give qubits a physical representation, in which they retain their quantum properties.

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BASIC QUESTION

- System

— The qubits can evolve as desired.

BASIC QUESTION

- Preparation and initial states

— We must be able to prepare qubits in some specified set of initial states.

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BASIC QUESTION

- Measurement

— We must be able to measure the final output state of the system.

INTRODUCTION

CHALENGER

— The experimental realization of these basic requirements are often partially met.

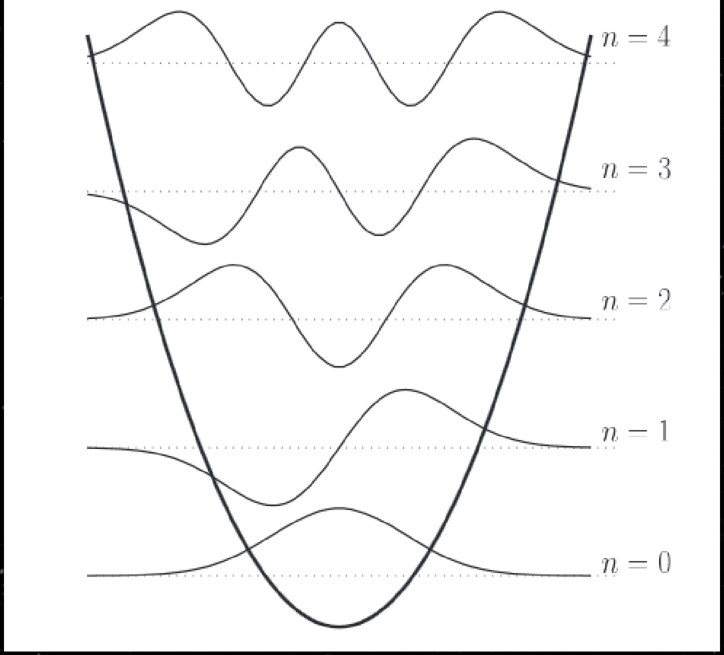
EXAMPLES

1. A single **<u>nuclear spin</u>** can be a very good qubit because superpositions of being aligned with or against an external magnetic field can last a long time.

But it can be difficult to build a quantum computer from nuclear spins because their coupling to the world is so small that it is hard to measure the orientation of a Single nuclei.

EXAMPLES

2. Qubit representation for Harmonic Oscillator
QC are the energy levels (n = 0, 1, 2, ...)

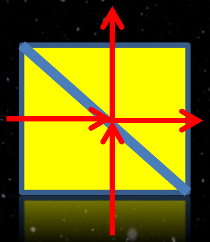


INTRODUCTION

EXAMPLES

3. Qubit representation for Optical photon QC-- light polarization

Gates → beamspliters



Beamspliters → piece of glass which reflects and transmits a fraction of incident light

The two inputs and two outputs of this device are related by

EXAMPLES

Beamspliters

$$a_{out} = a_{in} \cos\theta + b_{in} \sin\theta$$
$$b_{out} = -a_{in} \sin\theta + b_{in} \cos\theta$$

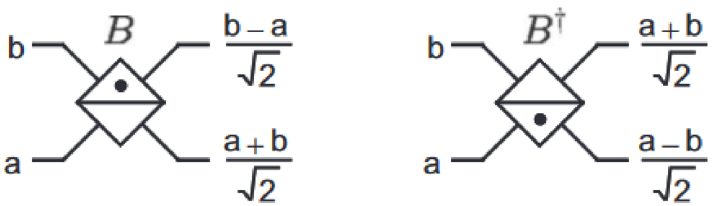


Figure 7.3. Schematic of an optical beamsplitter, showing the two input ports, the two output ports, and the phase conventions for a 50/50 beamsplitter ($\theta = \pi/4$). The beamsplitter on the right is the inverse of the one on the left (the two are distinguished by the dot drawn inside). The input-output relations for the mode operators a and b are given for $\theta = \pi/4$.

EXAMPLES

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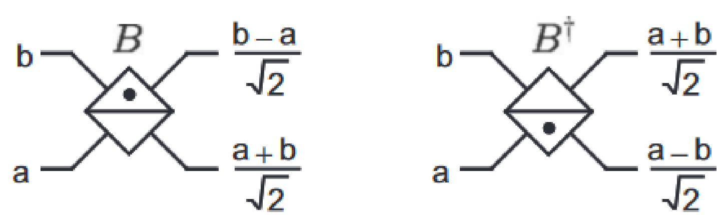


HADAMARD GATE → $|0\rangle \mapsto \frac{|0\rangle+|1\rangle}{\sqrt{2}}$ and $|1\rangle \mapsto \frac{|0\rangle-|1\rangle}{\sqrt{2}}$

Figure 7.3. Schematic of an optical beamsplitter, showing the two input ports, the two output ports, and the phase conventions for a 50/50 beamsplitter ($\theta = \pi/4$). The beamsplitter on the right is the inverse of the one on the left (the two are distinguished by the dot drawn inside). The input-output relations for the mode operators a and b are given for $\theta = \pi/4$.

In general

A quantum computer has to be well isolated in order to retain its quantum properties.

But at the same time qubits have to be acessible.

So that they can be manipulated to perform a computation and to read out the results.

Why we believe quibits exists in nature?

The qubit is a fundamental element for quantum computation and quantum information.

Why we believe qubits exists in nature?

How do we know that systems with properties of qubits exists in nature?

Why we believe qubits exists in nature?

A very famous experiment indicating the quibit* structure was conceived by Stern (1921) and performed with Gerlach (1922) in Frankfurt.

*However by that time it was not mention about the existence of qubits.

In fact, the idea of qubits would appear years later.

In the original experiment hot atoms were beamed from an oven throught a magnetic field.

This field causes the atoms to be deflected and then the position of each atom was recorded.

Stern-Gerlach Experiment

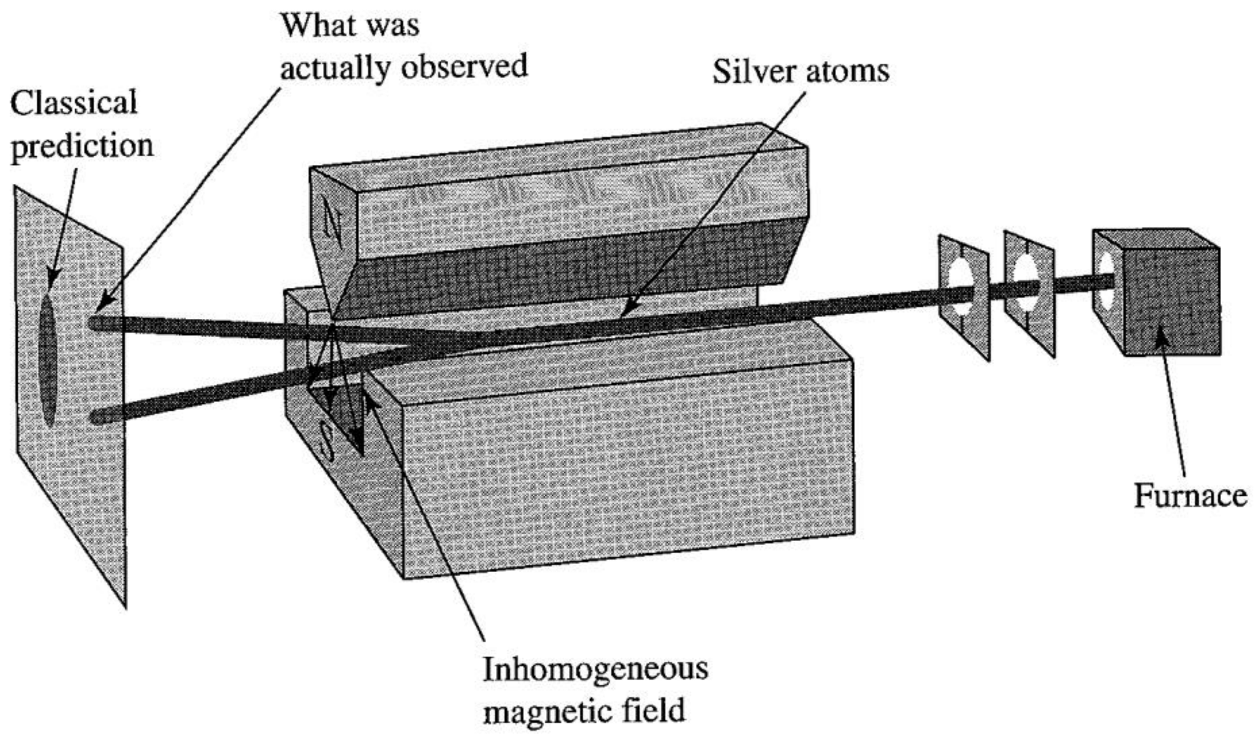


FIGURE 1.1 The Stern-Gerlach experiment.

Stern-Gerlach Experiment

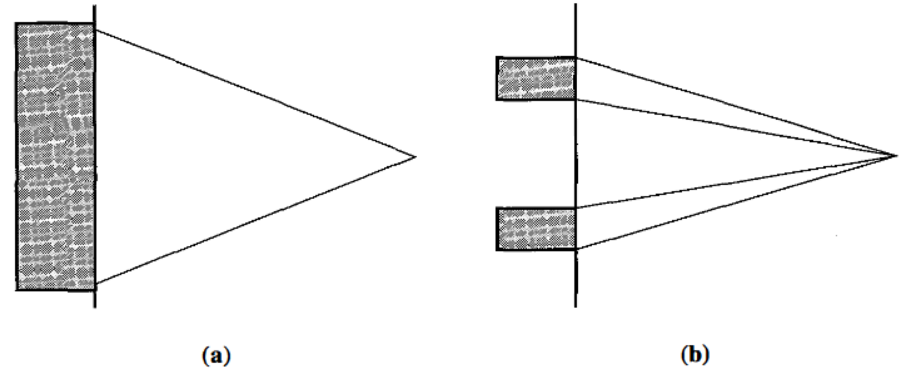
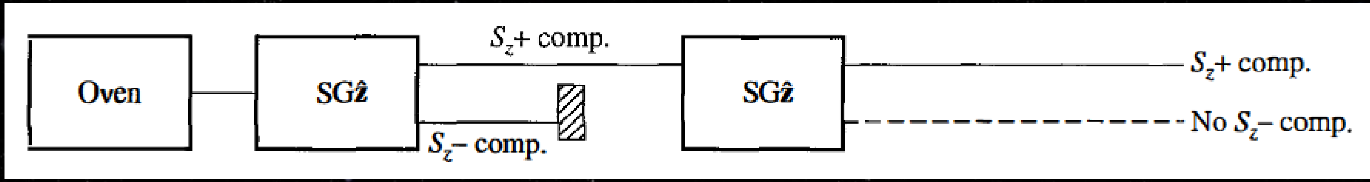


FIGURE 1.2 (a) Classical physics prediction for results from the Stern-Gerlach experiment. The beam should have been spread out vertically, over a distance corresponding to the range of values of the magnetic moment times the cosine of the orientation angle. Stern and Gerlach, however, observed the result in (b), namely that only two orientations of the magnetic moment manifested themselves. These two orientations did not span the entire expected range.

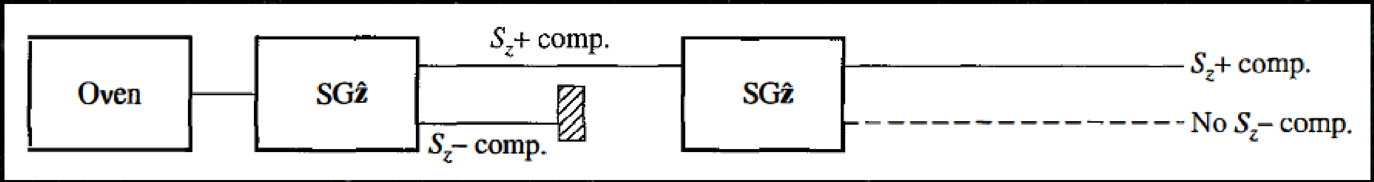
Modern Quantum Mechanics – Sakurai & Napolitano

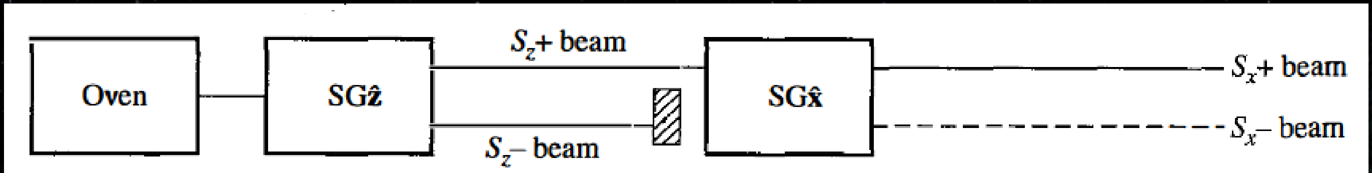
Sequential SG Experiments



No Surprise! Since we have na up spin its natural it remains up

Sequential SG Experiments





50% of the atoms in the S_z+ beam coming out from the first apparatus is characterized by the couple (S_z+ , S_x+), and 50% by (S_z+ , S_x-) ???

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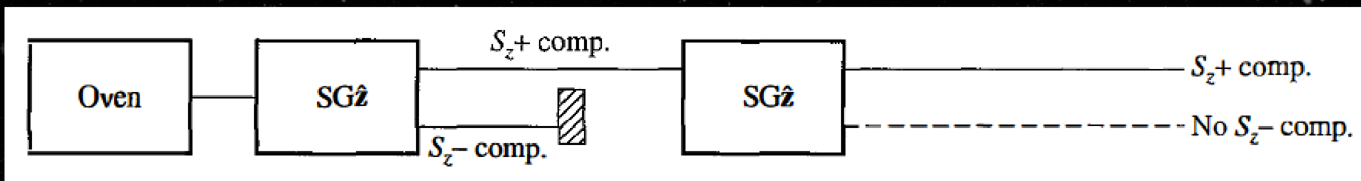
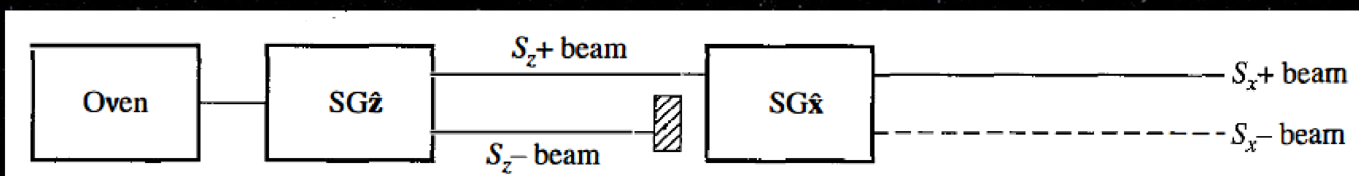
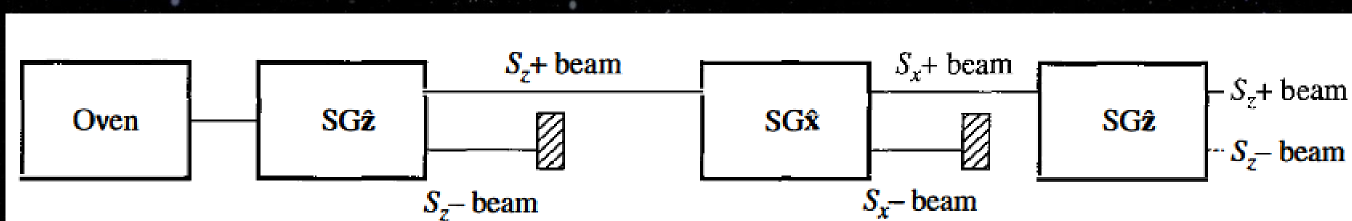
Sequential SG Experiments







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- The qubit model provides a good explanation for this experiment

$$Sz+ \rightarrow |0>$$

$$Sz- \rightarrow |1>$$

$$Sx+ \rightarrow (|0> + |1>) / \sqrt{2}$$

$$Sx- \rightarrow (|0> - |1>) / \sqrt{2}$$

- This example illustrates how qubits could be believable to model systems in Nature

COMING NEXT …

- History of Quantum Mechanics and Quantum Computation
- Mathematical tools of Quantum Mechanics
- Postulates of Quantum Mechanics
- Quantum Computers – Physical Realization