

Stern-Gerlach experiment

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Abstract

Studying the connection between quantum computing and classical physics

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1 Setup

We are walking through the [Building a quantum lock using phase kickback](#) tutorial by Danial Motlagh.

Python

```
import pennylane as qml
import numpy as np
import matplotlib.pyplot as plt
qml.drawer.use_style("black_white")
```

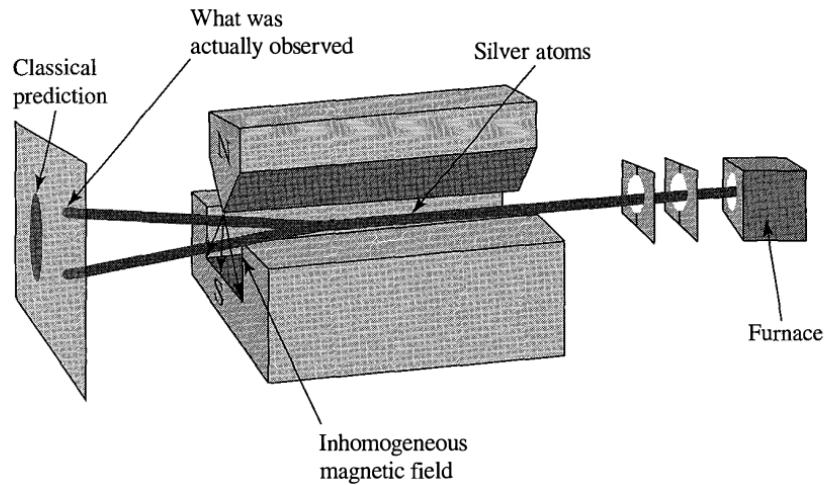
Result

2 Conversation

2.1 General information

User:

Hi AI. I'd like to study the connection between physics and quantum computing. Please tell me about the Stern-Gerlach experiment.



AI:

The Stern-Gerlach experiment is a fundamental milestone in quantum physics that demonstrates the quantization of angular momentum, a key concept with profound implications for quantum computing and quantum mechanics. Here's an overview of the experiment and its significance:

1. The Experiment Setup

The experiment involves sending a beam of silver atoms through a non-uniform magnetic field. These atoms possess an intrinsic angular momentum called *spin*, which is an internal quantum property.

2. Magnetic Field Interaction

The inhomogeneous magnetic field interacts with the magnetic moment of the silver atoms, causing them to be deflected. Classical physics would predict a continuous distribution of deflection corresponding to a continuous range of angular momenta.

3. Quantized Outcomes

However, the results showed that rather than a continuous spread, the beam splits into discrete lines, typically two distinct spots. This demonstrated the quantum property of spin, where only quantized values (in this case, $\pm \frac{1}{2}\hbar$ for spin- $\frac{1}{2}$ particles) are possible.

4. Wave-Particle Duality and Quantum Measurement

The Stern-Gerlach experiment provides direct evidence of the quantized nature of quantum systems and the principle of quantum superposition. When not measured, the spin state can be a combination of possible outcomes until a measurement collapses it to a specific value.

5. Implications for Quantum Computing

In quantum computing, the binary nature of spin measurements parallels the operation of qubits, which exist in superpositions of states until measured. This process underlies quantum gates and entanglement, essential elements of quantum circuits.

The Stern-Gerlach experiment is, therefore, a cornerstone demonstration of quantum mechanics, highlighting how quantum systems behave fundamentally differently from classical expectations. It establishes foundational concepts, such as quantum state measurement and spin, that are critical for understanding and developing quantum technologies like quantum computing.

2.2 Silver atom

User:

Tell me more please about the silver atoms. Why do their spin and magnetic momentum are connected?

AI:

The relationship between spin and magnetic moment in silver atoms, as well as in other atoms, is a consequence of the underlying quantum mechanics. Here's a deeper look into why these properties are connected:

1. Electron Spin

Spin is an intrinsic form of angular momentum carried by electrons. It is a purely quantum mechanical property with no classical analogue. Electrons have a spin of $\pm\frac{1}{2}$ in units of \hbar , the reduced Planck constant.

2. Magnetic Moment

The magnetic moment arises from the angular momentum of charged particles. Since electrons have a charge and also possess spin, they generate a magnetic moment. This is similar to how a classical charged particle moving in a loop generates a magnetic field.

3. Quantum Description of Atomic Magnetic Moment

In atoms, the total magnetic moment results from both the orbital angular momentum and spin of electrons. For silver atoms in the Stern-Gerlach experiment, the unpaired outer electron primarily contributes to the magnetic moment because its motion and spin create a small loop of current with a north and a south magnetic pole.

4. Connection in Silver Atoms

Silver atoms, specifically, have a single unpaired electron in their outermost shell - the 5s electron. The majority of its electrons' magnetic moments cancel out because they are paired and have opposite spins. Therefore, the overall magnetic behavior of the atom is predominantly determined by this unpaired electron.

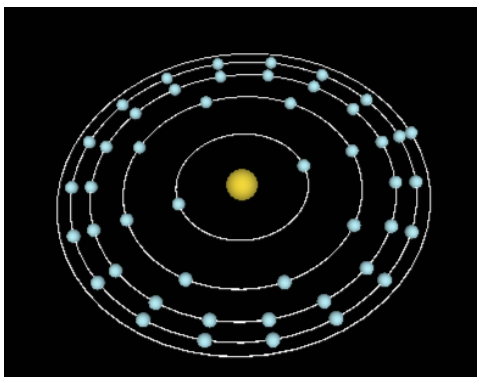
5. Role in the Stern-Gerlach Experiment

In the Stern-Gerlach experiment, a beam of neutral silver atoms is used because of this single unpaired electron, which provides a clear and measurable magnetic moment. When such atoms pass through a non-uniform magnetic field, the interaction of the unpaired electron's magnetic moment with the field causes the beam to split according to the quantized spin states of the electron, demonstrating the quantization of angular momentum.

In quantum mechanics, the intrinsic property of electron spin and its associated magnetic moment are fundamentally linked, leading to observable phenomena such as the deflection observed in the Stern-Gerlach experiment. This connection helps illustrate the core quantum principles that also underpin behaviors in quantum computing, such as the manipulation of qubit states.

User:

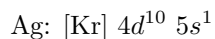
Can you suggest a visualization of a silver atom? I'd like to see its electron configuration. Do you know a paper which describes this in great details?



AI:

To visualize a silver atom and understand its electron configuration, we can create a simple depiction using the periodic table's information on electron shells and subshells. The electron configuration gives us insight into which subshells the electrons populate.

The electron configuration of a silver (Ag) atom is:



Here's a breakdown of this configuration:

- The [Kr] indicates that silver's configuration starts like Krypton with 36 electrons.
- The $4d^{10}$ subshell is fully filled with 10 electrons.
- The $5s^1$ subshell contains one unpaired electron.

Given the configuration, the focus for visualizing the atom, especially considering properties relevant to the Stern-Gerlach experiment or any chemical reactivity, would be on the $5s^1$ electron which is the outermost and unpaired electron. This electron contributes the most to the magnetic moment due to its spin.

To depict this visually, you could draw a nucleus at the center, surrounded by concentric circles representing shells (energy levels). The inner shells can showcase electrons filling up to Krypton's configuration. The outermost shell would show the 5th shell with a single electron. This visualization highlights the presence of the lone unpaired 5s electron.

Regarding literature, a recommended resource for detailed descriptions of atomic structures, including electron configurations, is standard chemistry or quantum mechanics textbooks. For a detailed scientific paper exploring silver atoms specifically, I suggest looking into articles published in journals of computational chemistry or atomic physics, such as:

- "Journal of Chemical Physics"
- "Physical Review A"

These journals often provide in-depth discussions on atomic configurations, potential energy surfaces, and computational models which can offer detailed insights into the structure and behavior of specific atoms like silver.

User:

Can you comment this: In atoms, the total magnetic moment results from both the orbital angular momentum and spin of electrons. What simplest atom is used in physics textbooks to illustrate this?

AI:

In atoms, the total magnetic moment arises due to contributions from two main sources: the orbital angular momentum of electrons (which is the result of their motion around the nucleus) and the intrinsic spin of electrons (a fundamental quantum property). The simplest atom often used in physics textbooks to illustrate these concepts is the hydrogen atom.

- **Hydrogen Atom**

The hydrogen atom is the simplest atom, consisting of a single electron orbiting a single proton. Despite its simplicity, it is a critical example for studying fundamental quantum mechanical principles because it exhibits both types of angular momentum: orbital and spin.

- **Orbital Angular Momentum**

The electron in the hydrogen atom moves in quantized orbits around the nucleus, characterized by the angular momentum quantum number l . The possible values of l range from 0 to $n - 1$, where n is the principal quantum number.

- **Spin Angular Momentum**

The electron also possesses spin, an intrinsic form of angular momentum with only two possible states: $+\frac{1}{2}$ (spin-up) and $-\frac{1}{2}$ (spin-down).

- **Magnetic Moment**

Both the orbital motion and spin contribute to the magnetic moment of the atom, which affects how it interacts with external magnetic fields. The total magnetic moment is a vector sum of the orbital and spin magnetic moments.

- **Textbook Example**

The hydrogen atom often serves as the starting point for introducing quantum mechanics concepts. It provides clear motivation for the development of quantum mechanical models, such as the Schrödinger equation, and sets the foundation for understanding more complex atomic structures.

The hydrogen atom's simplicity makes it ideal for exploring these fundamental quantum properties and their consequences, which can then be extended to understand atoms with more electrons.

User:

What are angular momentum quantum number l and the principal quantum number?

AI:

In quantum mechanics, quantum numbers are used to describe the properties of atomic orbitals and the electrons within them. Two important quantum numbers are the principal quantum number (n) and the angular momentum quantum number (l). Let's explore both:

- **Principal Quantum Number (n)**

- Represents the main energy level or shell of an electron in an atom.
- Determines the average distance of the electron from the nucleus: higher n values correspond to higher energy levels, and thus electrons are further from the nucleus.
- Takes positive integer values: $n = 1, 2, 3, \dots$
- The energy of an electron is mainly determined by n , especially in hydrogen-like atoms.

- **Angular Momentum Quantum Number (l)**

- Associated with the shape of the electron's orbital. It describes the angular distribution of the electron cloud.
- Takes integer values from 0 to $n - 1$ for each principal quantum number.
- The value of l determines the subshell or sublevel: - $l = 0$ corresponds to the s subshell, - $l = 1$ corresponds to the p subshell, - $l = 2$ corresponds to the d subshell, - $l = 3$ corresponds to the f subshell, and so on.
- Each subshell can hold a different number of electrons: $2(2l + 1)$.

The quantum numbers allow us to describe and predict the electron configuration of atoms, which in turn explains chemical bonding and atomic properties. Both n and l are crucial for understanding the structure of atoms and the placement of electrons within the periodic table.

User:

In silver, why does the spin of the last electron contribute to the magnetic momentum of the whole atom? What about its orbital momentum?

AI:

In a silver atom, the contribution of the spin of the last electron to the magnetic moment is significant

because of the specific electron configuration of the atom. Let's explore why the spin is prominent and the role of orbital momentum:

- **Electron Configuration of Silver**

- The ground state electron configuration of silver (Ag) is $[\text{Kr}] 4d^{10} 5s^1$.
- The $4d^{10}$ subshell is fully filled, and the $5s$ subshell contains one unpaired electron.

- **Spin Contribution**

- The unpaired $5s$ electron adds a net spin angular momentum to the atom because it is not paired with another electron that would negate its magnetic moment.
- The spin of an unpaired electron generates a magnetic moment that contributes directly to the atom's overall magnetic properties.

- **Orbital Angular Momentum**

- In the case of the $5s$ electron, the orbital angular momentum quantum number l is 0 (since it is in an s orbital). This means that its contribution to the orbital angular momentum is zero.
- The filled $4d$ subshell, having all d orbitals completely filled, effectively cancels out its orbital angular momentum contributions. Electrons in filled subshells or orbitals align in such a way that their magnetic moments cancel out.

- **Overall Magnetic Moment of Silver**

- Because the d subshell is fully filled and does not contribute a net magnetic moment, the only significant contribution comes from the spin of the unpaired $5s$ electron.
- Therefore, the total magnetic moment is primarily due to the spin of this last electron, rather than from contributions of orbital angular momentum.

Thus, in an atom like silver, the magnetic properties are dominantly influenced by spin, particularly when subshells with higher angular momentum are entirely filled, negating orbital contributions.

User:

But in Hydrogen we also have a single s electron. What about its orbital momentum?

AI:

In a hydrogen atom, which consists of a single electron orbiting a single proton, both the spin and orbital angular momenta play important roles in its quantum mechanical description. However, the specific properties of an s orbital affect these contributions. Let's delve into this:

- **Electron in Hydrogen:**

- The electron in hydrogen occupies the $1s$ orbital in its ground state.

- This configuration is denoted as $1s^1$.
- **Orbital Angular Momentum:**
 - The orbital angular momentum quantum number l for an s orbital is always 0.
 - Since $l = 0$, the orbital angular momentum $L = \sqrt{l(l+1)}\hbar = 0$.
 - Consequently, the orbital contribution to the magnetic moment is zero in the ground state of hydrogen.
- **Spin Angular Momentum:**
 - The electron has an intrinsic spin characterized by the spin quantum number $s = \frac{1}{2}$.
 - This non-zero spin results in a spin angular momentum $S = \sqrt{s(s+1)}\hbar$ and gives rise to a magnetic moment.
 - The magnetic moment due to spin is not dependent on the orbital type; instead, it arises from the intrinsic property of the electron itself.

Overall, in the hydrogen atom, although the s orbital provides no orbital angular momentum due to $l = 0$, the electron's spin contributes significantly to the atom's magnetic properties. This underscores the distinct roles and intrinsic properties of spin and orbital momentum in quantum mechanics.