Observing the spin of free electrons in action
(Stern-Gerlach experiment by free electrons)

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Abstract
Stern-Gerlach experiment by free electron is very important experiment because it answered some questions that remain unanswered for almost a century. Bohr and Pauli considered its objective observation as impossible while some other scientists considered such observation as possible. The experiment on free electrons has not been conducted so far because the high magnetic field gradient predicted there was thought as impossible to generate. This paper proves that it is not only possible but also observable using a high vacuum lamp which is deionized well. To obtain a high magnetic field gradient, it is not necessary to have a very strong magnetic field and it is possible to observe the phenomenon using a very sharp pointed magnet and adjusting the voltage in a certain distance from free electron beams.

Introduction
The concept of electron spin was first proposed by Samuel Goudsmit, George Uhlenbeck, and Wolfgang Pauli in 1920, suggesting a physical interpretation of particles, spinning around their own axis. They stated that an intrinsically angular momentum depends on any electron, quite independent of the orbit angular momentum. This intrinsic momentum is called electron spin.\footnote{1} Spin is considered as a fundamental property of subatomic particles, which has no classical equivalent and it is considered a quantum property. To help visualize the model, consider it as an object in space which continuously rotates around an axis. To describe electron spin, assume a magnetic moment. If an electron exists in an external magnetic field with its permanent magnetic moment, its spin is expected to be quantized. It means that the spin magnetic moment and spin angular momentum will be restricted to certain orientations. There are only two intrinsic spin states for electrons. In general, the electron magnetic moment is expressed as $\mu = \frac{e g}{2m} S$, in which $e$ represents the electron charge; $g$ is gyromagnetic ratio; $m$ is the mass of the electron, and $S$ is the electron spin operator. The constant term in electrons magnetic moment is called Bohr magneton constant. When electrons are placed in an inhomogeneous magnetic field, a force is exerted from the field. This force is exerted through a gradient of potential energy (equation 1).

$$F = -\nabla U = -\nabla (\mu . B)$$

In 1921-1922, Otto Stern suggested that magnetic dipole moments of various atoms be measured through detection of the atomic beam deflection in an inhomogeneous magnetic field.\footnote{2} he had significantly developed the techniques of atomic and molecular beams during two years of Einstein’s assistance. This led him to conduct an experiment in collaboration with Walter Gerlach in which they steamed silver atoms in a furnace in a vacuum, passed them through an inhomogeneous magnetic field, and finally registered them on a screen. Indeed, electron spin in silver atoms is related to the effect of the electron spin in the last atomic orbit, and the effect of nucleus and other electrons are ignored. Lorentz force is largely inhibited due to use of atoms in Stern-Gerlach experiment. Bohr, Pauli, and Mott believed that given Bohr magneton coefficient compared to the gradient of the magnetic field, such a phenomenon may not be seen in reality. The impossibility of observation of free electron spin is a general principle and this experiment can never be expressed in terms of the classical approach.\footnote{3} Bohr and Pauli also stated that:\footnote{4} “It is impossible to observe the spin of the electron, separated fully from its orbital momentum, by means of experiments based on the concept of classical particle trajectories”.

\begin{thebibliography}{99}
\bibitem{1} PCT Support Registration Office, Patent Name: Electron Intrinsic Spin Analyzer, Inventor: Hosein Majlesi
\bibitem{2} Pursuing and confirming the invention by Khojeh Nasir Toosi’s Department of Physics (University)
\bibitem{3} Patent Link: http://ip.ssu.ir/Patent/SearchResult.aspx?DecNo=139350140003006698&RN=84973
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Sixth Solvay Conference in 1930, Brillouin proposed a model of an inhomogeneous magnetic field where primary fields were symmetric and along the beam path. It was significantly different from the geometry of the Stern-Gerlach's apparatus.[8] Bohr and Pauli explicitly opposed his model.[9] They rejected it using a semi-classical approximation cited in Mott, Massley, and Klemperer studies.[10], [11], [12]. It should be noted that Lorentz force exists in the system and it is not removable; moreover, its direction differs from the spin force. Lorentz force is certainly greater than the spin force. Electrons are separated due to dipole spatial interaction of the magnetic field with wave function assigned to electrons. In other words, due to the limited width of the beam, they deviate to the left or right when influenced by Lorentz force, so the spin force causes the beams to separate. So wave function spin separation, resulting from the interaction of the dipole magnetic field, may fade owing to the circuit magnetic effect. It may not reflect the true nature of the spin. The combination of Newtonian mechanics and quantum mechanics in this case causes any arguments to be regarded with uncertainty. Given the relativistic nature of electron spin, it is imperative that formulation of quantum be appropriate and an analogy be drawn between classical and quantum nature of the electron spin so that more accurate data are obtained about the system and position of the particles. Measuring the system is aimed to obtain data on any state of the system. As already stated, Lorentz force and the dividing force of the spin are both involved in Stern-Gerlach experiment at the same time, and it is important to set them apart. Pauli holds a prejudiced opinion that electron spin can never be observed yet Bohr had a more cautious view and said:[13] "I have sometimes thought of the problem of the realisation of the electron polarization, and after all I am quite prepared that such a polarization might be observable. [O]ur argument tells ... not that the closer quantum-theoretical treatment will never give a positive effect". When Bohr and Pauli suggested the impossibility of the observation, almost all scientists had acknowledged it, until Dehmelt conducted a controversial experiment in 1988 and gained an electron magnetic momentum outside atomic framework which ran contrary to what predicted by Bohr and Pauli.[14], [15] So far, many questions have been raised about the possibility of Stern-Gerlach experiment with electrons.

Is it really possible to measure electron spin?

Various studies were carried out about how to remove Lorentz force, most notably Brillouin’s model. A full analysis of Quantum Wave Theory reveals that it is quite possible. Since 1997, several papers have been published in this regard. Although Bohr and Pauli’s arguments received many physicist’s confirmation, it is important to take Bohr and Pauli’s views into account. For example, in 1997 Batelaan, Gay, and Schwendiman wrote an article in which they used Pauli’s argument to reject Brillouin’s model and given the semi-classical approximation, they showed observing the electron spin possible.[16] In 1998, Rutherford and Grobe drew on Dirac numerical equations to demonstrate that measurement of electron spin is hard, yet possible to be observed.[17] In 1999, Garraway and Stenholm used wave packet analysis in quantum mechanics to prove that Stern-Gerlach phenomenon is possible to be observed for free electrons.[18] In 2001, Gallup and Batelaan demonstrated that given the semi-classical approximation (WKB) spin separation is possible.[19] In 2011 Scot McGregor, Roger Bach and Batelaan proposed a solution in their essay based on Brillouin’s model.[20]. You will find a geometric and mathematical solution which predicts observing the spin of free electrons at a particular point in space using a very sharp magnet (this solution is based on Stern-Gerlach experiment by potassium atomic beams) and then the experiment with electrons will be explained in detail.

Description And Technical Methods

As stated before, in order to separate the electron’s spins, Lorentz force must be controlled and a proper and inhomogeneous magnetic field must be applied to separate the electrons’ spins in practice. However, as an electron has a very low mass, it seems impossible for single electrons to control Lorentz force. So, according to Bohr and Pauli, a very high magnetic field gradient is required and any proposed solution should be able to explain the related classical approach. If we consider that electron’s travel in a straight line along with X axis in the space before applying a magnetic field, we can find Lorentz force from the following equation: \( F = e \times B + eE \), in which the direction of its first term can be found based on the speed of electrons flow and direction of the magnetic field applied. Moreover, as there is no magnetic monopole \( \nabla \cdot B = 0 \) therefore: \( \frac{\partial B}{\partial t} = -\nabla \times E \) So, concerning Lorentz force and spin separating force, it is expected to get the separation from classical approach: (equation 2).

\[
Z = \frac{1}{2}at^2 + vt = \frac{1}{2}\left(\frac{e}{m}\right) \cdot \nabla B |t^2 + vt
\]

In this equation, \( vt \) term is explicitly ignored. So, only this first term (eq.2) would be considered meaningful. In equation (eq.2), time is stated as \( t = \frac{1}{n} \) in which \( L \) the interaction distance between electrons and magnetic field is a constant value and \( v \) stands for electron’s speed. Of course, concerning the speed of electrons in vacuum, it is not much far-fetched to
consider magnetic field gradient as the only influential factor in the above equation. So, regarding the numerical value of $\mu = 10^7$, only the value of two parameters of electron speed and magnetic field gradient is unknown in this equation (eq.2) which is very important to be found. By axis analysis we can find the following simplified form of the gradient: (equation 3).

$$\nabla (F.G) =$$

$$= (F.\nabla) G + F \times (\nabla \times G) + (G.\nabla) F + G \times (\nabla \times F)$$

Regarding this equation, the potential gradient phrase will be in the following simplified form: (equation 4).

$$\nabla (\mu . B) =$$

$$= (\mu . \nabla) B + \mu \times (\nabla \times B) + (B.\nabla) \mu + B \times (\nabla \times \mu)$$

As $\mu$ is a constant value, its related differentials will be zero. Besides, as zero value of phrase $\mu \times (\nabla \times B)$ depends on phrase $(\nabla \times B)$, based on Maxwell’s equations we will have: (equation 5).

$$\nabla \times B = \frac{1}{c^2} \frac{\partial E}{\partial t} = \frac{\omega E}{c^2} = \frac{2\pi fE}{c^2}$$

Therefore, if we use an alternative electric field with a term $\frac{\partial E}{\partial t}$ will not be zero but $\frac{\partial E}{\partial t} = \omega E = 2\pi fE$ so the spin force will be as follow: (equation 6).

$$F = -\nabla (\mu . B) = - \left( \mu (\nabla B) + \mu \times \left( \frac{1}{c^2} \frac{\partial E}{\partial t} \right) \right)$$

$$= - \left( \mu (\nabla B) + \mu \times \left( \frac{2\pi fE}{c^2} \right) \right)$$

It can be expected that a term is added to spin separating force. However, as electric field is not an important factor in classical Stern-Gerlach experiment on silver atoms, so we will have $\nabla \times B = 0$. Hence, only the term $\mu (\nabla B)$ is left in our experiment which causes the dispersion of beams. Electrons cannot be evaporated like silver atoms but they can be easily separated by applying an appropriate voltage from hot Tungsten in a high vacuum and appropriately deionizes condition and then lead them flow through parallel plates. The mass of an electron is much less than a silver atom mass, so the speed of electrons is much greater than the speed of silver atoms. Electric field is also unavoidable which will somehow complicate the issue. Hence, Lorentz force is highly influential and cannot easily be ignored in our calculations. Because much stronger electric field is required to remove Lorentz force from the system which may call for relativistic relations. That is why it’s not been included in calculations so far. We used a high vacuum lamp to observe the intrinsic spin of electrons (figure a-1). This lamp was made of three main parts: a high vacuum glass bulb (which is properly deionized), an electron gun and a phosphorescent sheet which includes high purity phosphorus. When the lamp was vacuumized, it is deionized using a diffusion pump. But you know that ions will not be totally removed from system; so atoms and molecules, even on a very small scale, are ionized and become highly reactive when electric field is applied. They react with phosphorus atoms which have been activated and make these atoms lose their initial purity and nature and the sheet is so called burned out. So deionization is almost a vital process and a certain type of alloy is used in higher levels to do deionization. This makes it possible to deionize the lamp through indirect heating. This alloy which is called Getter stands against the electron gun (figure 1-b, 1-c).

![Figure 1: Figure a shows a used lamp; Figure b,c shows the structure of a electron gun and Getter.](image)

Besides, electrons and ions flow in opposite directions in the electric field and due to mass flow of electrons influenced by high voltage, we can ignore the presence of ions in the lamp. Electron beams, after being separated from filament, are paralleled by Grid Plates of gun which play the same role of collimators in Stern-Gerlach experiment, and then are shot to phosphorescent plate and hit it and cause illumination. The most sensitive part of the lamp is the electron gun and the related parts set much sensitively. Generally, this electron gun has some similarities and differences with
Stern-Gerlach furnace. Both include some thermodynamic preparations for separation. When an electron beam is influenced by an appropriate potential difference, it will hit the screen and distributed in Gaussian symmetric form. Of course, it is very important to set carefully the intensity by which beams hit the screen to obtain an appropriate Gaussian form. When an electron beam is influenced by an inhomogeneous external magnetic field, spin elements are separated from each other. But two things are important here about electrons: firstly, as the mass of electron is small, Lorentz force cannot be easily removed. Secondly, obtaining a high magnetic field gradient will be a basic problem. Concerning the first problem, Lorentz force cannot be totally removed from the system but its effect on observation can be reduced to a great extent. In case of the second problem, there arises the important question that:

**Is it necessary to have a very high magnetic field to produce a very high gradient?** No. The value of magnetic field gradient is very high and indefinite near sharp pointed objects. Concerning this point, a simple geometric solution can be introduced. It is introduced based on the geometry used in magnets in the experiment conducted by Stern-Gerlach using Potassium atom beams\[^{23, 24}\]. Its truth was also proved in practice. Consider a circle as the center of all geometrical calculations (figure 2-a) to which enters a magnet with the radius a (1) and a second magnet is tangential to the circle’s external plane (2). Calculation of magnetic field lines is made using two points of intersection of the magnet (1) with circle calculator. Since high gradient is not required in Stern-Gerlach classical experiment using potassium atom beams, radius of the lower circle(magnet(1)) is a little smaller than the radius of main circle calculator. According to the above mentioned in\[^{24}\], magnetic field gradient will finally be calculated in the following form (for the center of circle calculator) (equation 7)

\[
\frac{\partial H}{\partial z} = 0.968 \frac{H}{a}
\]

and the simplified form will be as: (equation 8)

\[
\frac{\partial B}{\partial z} = \frac{B}{a}
\]

In this equation (eq.8), final magnetic field gradient has an inverse relationship with the radius of internal circle and yet a direct relationship with the value of magnetic field applied on magnets. Although this equation seems simple, it can help us understand how much magnetic field gradient varies with the variation of internal magnet radius (1). Now suppose that the internal magnet radius (1) goes to zero(limited to zero), then the radius of circle will be very low in equation an in fact we will have a very sharp magnet, the small number in denominator will turn to a large coefficient in the field size, and the final inhomogeneous magnetic field gradient will significantly increase. Actually, such magnets were designed (Figure 2-c, 2-b) and one of them was sharp pointed so that when located on a certain point separation of spins could be observed. It is noteworthy that the direction of magnetic field lines is an important factor for recognizing this phenomenon. The sharp point of one magnet must be N and the curve end of another one must be S.

![Figure 2](https://physik.unibas.ch/Praktikum/VPPI/SternGerlach/5_1_11.pdf)
quality of spin separation depends on three factors: frequency of electric field, and the distance of magnets from exit aperture of electron gun. A question may come to your mind that:

Can objective observation be the result of Lorentz force? Since the mass of electrons and the electric field is very small, Lorentz force cannot be removed from system but it can be observed simultaneously in the experiment and distinguished according to the extent which electron beams travel. What can be observed in practice is that when inhomogeneous magnetic field is applied, the initial single electron beam split into two beams very close to each other (10 micro meter to 100 micro meter) and the two beams travel together(at the one time). Besides, due to size of the magnetic field used in the experiment, Lorentz force exerted a deviation of some millimeters or about one or some centimeters, the extent of which can be easily distinguished from separating force of electron’s spin.

Beams are split into two beams only when the applied magnetic field is inhomogeneous. (figure 3-a, 3-b).

Figure 3: Figure 3-a represents an electron beam before applying an inhomogeneous magnetic field. Figure b represents a pair-beam electron after applying the inhomogeneous magnetic field (using a stationary magnet) and the two beams travel together.

May the objective observation result from variation of electron velocity distribution? (different velocity) It’s important note. If there is variation in electron velocity distribution, it may seem as separation(?)?

But this may never happen in this experiment as the frequency of electric field is constant(according to the electron velocity order). to This can be tested in practice and convinced that if two flat magnets are used instead of gradient magnets, we can expect that electrons travel exactly according to Lorentz force and if there is variation in electron velocity distribution, it will be proved well. This hypothesis was tested and found that when flat magnets are used: the single-beams merely travel according to Lorentz force and no split was reported. So this would occur only in the presence of gradient and all electrons have the same speed.

So, Beams are split into two beams only when the applied magnetic field is inhomogeneous.

Does the direction of electric field lines change? No, electric field voltage is fed and strengthened by diodes and capacitors.

We observed that along the widthwise direction of electrons emission, too much static electricity is generated which is a good evidence that suggests it is very likely that electrons do not travel in a quite direct path. Besides, this can clearly be observed when voltage is reduced to a certain extent. The charge of static electricity around the lamp greatly affect the path of electrons so that it requires to place objects close to the earth in order to eliminate this effect and avoid any intervention in the result. As voltage increases, the quality of paired image tends to decrease so that there will no longer be enough resolution. When the voltage is very low, no image can be observed. It is evident that as frequency of electric field changes, the length of electron-bunch train emitted from gun will change and this in turn affect the quality and resolution of the image. By applying an inhomogeneous magnetic field, distribution of Guassian beam changes. So far, all calculations were made based on the hypothesis that electrons travel through a direct path in the space which originates from a classical view. On the other hand, all calculations made on electron velocity so far focused on single electrons, while there is no single or individual electron in reality. So one consequence for holding this view would be to ignore coulomb force or other similar forces. Therefore, when some electrons travel together closely, the repulsion and attraction between them place them in a balanced distance to each other. If an electric field, under a certain voltage, make electrons move along the spiral pattern in space (figure 4-a) one can claim that electron impulses before applying the inhomogeneous magnetic field would not be merely limited to moving along the direction of electrons. But components of the impulse axis for each electron is polarized along with the screen for electrons flow. So the impulses will be significantly reduced along with the electron emission. Hence, it is evident that electrons will have much more time to interact with inhomogeneous magnetic field (figure 4-b) and we can see more separation distance which was seen in practice.
So what we know as drift velocity of electrons and is related to ($\approx 10^5 m/s$) can refer to the speed along with electrons emission not speed in its cross section. Of course more research is required to measure the actual speed in the cross section. Images obtained in this experiment conform a lot to the experiment simulated in some articles which used the wave packet concept.[18][22] Using a CCD camera and a similar system and do the fitting by matlab or some other professional software, we can prove its objective truth in practice. Voltage of the lamp used in our experiment ranged from 5kV to 25kV . Electrons velocity, energy range, and the related wave length have been discussed in table 1. unfortunately, due to the measuring instrument we reported voltage span.[21]

![Figure 4](image)

**Figure 4:** Figure 4-a represents the spiral path of electrons caused by interaction. Figure b shows the spiral path of electrons when confronted with inhomogeneous magnetic field.

| Accelerating Voltage of Electrons (m/sec) | Velocity of Electron (Kg) | Mass of Electrons (N*m) | Energy of Electron (m) |
|-----------------------------------------|---------------------------|------------------------|-----------------------|
| 5                                      | 4.19E+07                  | 9.11E-31               | 8.01E-16              |
| 6                                      | 4.59E+07                  | 9.11E-31               | 9.61E-16              |
| 7                                      | 4.96E+07                  | 9.11E-31               | 1.12E-15              |
| 8                                      | 5.30E+07                  | 9.11E-31               | 1.28E-15              |
| 9                                      | 5.63E+07                  | 9.11E-31               | 1.44E-15              |
| 10                                     | 5.93E+07                  | 9.11E-31               | 1.60E-15              |
| 12                                     | 6.50E+07                  | 9.11E-31               | 1.92E-15              |
| 13                                     | 6.76E+07                  | 9.11E-31               | 2.08E-15              |
| 14                                     | 7.02E+07                  | 9.11E-31               | 2.24E-15              |
| 15                                     | 7.26E+07                  | 9.11E-31               | 2.40E-15              |
| 16                                     | 7.50E+07                  | 9.11E-31               | 2.56E-15              |
| 17                                     | 7.73E+07                  | 9.11E-31               | 2.72E-15              |
| 18                                     | 7.96E+07                  | 9.11E-31               | 2.88E-15              |
| 19                                     | 8.17E+07                  | 9.11E-31               | 3.04E-15              |
| 20                                     | 8.39E+07                  | 9.11E-31               | 3.20E-15              |
| 21                                     | 8.59E+07                  | 9.11E-31               | 3.36E-15              |
| 22                                     | 8.80E+07                  | 9.11E-31               | 3.52E-15              |
| 23                                     | 8.99E+07                  | 9.11E-31               | 3.68E-15              |
| 24                                     | 9.19E+07                  | 9.11E-31               | 3.84E-15              |
| 25                                     | 9.38E+07                  | 9.11E-31               | 4.01E-15              |
| 26                                     | 9.56E+07                  | 9.11E-31               | 4.17E-15              |
| 27                                     | 9.75E+07                  | 9.11E-31               | 4.33E-15              |
| 28                                     | 9.92E+07                  | 9.11E-31               | 4.49E-15              |
| 29                                     | 1.01E+08                  | 9.11E-31               | 4.65E-15              |
| 30                                     | 1.03E+08                  | 9.11E-31               | 4.81E-15              |

| Wavelength (m) |
|----------------|
| 1.73E-11       |
| 1.58E-11       |
| 1.47E-11       |
| 1.37E-11       |
| 1.29E-11       |
| 1.23E-11       |
| 1.12E-11       |
| 1.08E-11       |
| 1.04E-11       |
| 1.00E-11       |
| 9.70E-12       |
| 9.41E-12       |
| 9.14E-12       |
| 8.90E-12       |
| 8.67E-12       |
| 8.46E-12       |
| 8.27E-12       |
| 8.09E-12       |
| 7.92E-12       |
| 7.76E-12       |
| 7.61E-12       |
| 7.46E-12       |
| 7.33E-12       |
| 7.20E-12       |
| 7.08E-12       |

Table 1: shows the values of voltage, velocity, mass, energy, impulse and wavelength.
Concerning the value of velocity which is from 
\(\approx 10^7 m/s\), so \(\gamma \approx 1\) (equation 8)

\[
\gamma = \frac{1}{\sqrt{1 - \left(\frac{v}{c}\right)^2}} = \frac{1}{\sqrt{1 - \left(\frac{\gamma\tau \approx 10^7}{c}\right)^2}} \approx 1
\]

so velocity cannot be proportional. The electric field will be \(\approx 10^5 V/m\) separation distance of electron beam is about \(\approx 10 \mu m\) to \(\approx 100 \mu m\). This separation can be observed in the following figures.

(figure 5)

Figure 5: Figure a,b,c,d represent the electron beam before applying inhomogeneous magnetic field. e,f,g,h represent the electron beam after applying inhomogeneous magnetic field recognized by dc current.

Spin separation can be better observed using a linearizer which creates a secondary inhomogeneous magnetic field (figure 6).

Figure 6: Figure a,b,c represent linearized electron beam before applying magnetic field. Figure d,e,f represent the electron beam which has turned to parallel lines after applying magnetic field.

Figure 7 displays a general view of the machine.

Results

Stern-Gerlach experiment using the electron beam had not already been performed and contrary to what Bohr and Pauli predicted, observation of electrons spin was not only possible but it also happened in practice and it conformed to classical equations as well. Spin separation occur within a certain voltage span so that if the electrons’ voltage is greater than a certain amount, the phenomenon cannot be observed due to the short time interaction between electrons and magnetic field and the image of separation does not have much resolution. If voltage is lower than a certain amount, beams will never approach the screen and there will be no image on the screen. To product a high magnetic field gradient does not necessarily require a strong magnetic field and it can be created within a certain distance from a sharp pointed magnet in a certain form. Besides, it was not enough to have only a high magnetic field gradient. It was also important to use an appropriate voltage. The quality of spin separation image
improves by adding three components and beams will be more distinguished: Frequency of electric field and the strength of magnetic field (degree of gradient of magnetic field) and increasing the distance of magnets from the exit aperture of electron gun, ... Contrary to what was expected before about certain voltage span, electrons do not travel in a direct path in the space due to coulomb force or other unknown forces. They are also emitted in the cross section and emit lots of static electricity charge around. it was very similar to simulations[18],[22] Electron beams can be observed with a better quality after separation using a linearizer. that objective observation requires your consideration of some technical points simultaneously.

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