About The Centenary of Spin Discovery

Celso Luis Levada[1], Tabata Vidal[2], Huemerson Maceti[3], Carlos Miranda Awano[4], Bruno Sagioro Zaniboni[5], Ivan José Lautenschleguer[6], Miriam de Magalhães Oliveira Levada[7]

[1,2,3,4,5,6] *Herminio Ometto Foundation-Fho/Uniararas-Engineering Nucleus- Brazil*
[2,3] *Colégio Puríssimo Coração De Maria - Highschool - Rio Claro / Sp - Brazil*
[7] *Herminio Ometto Foundation-Fho/Uniararas-Nucleus of Health-Brazil*

Abstract: **In 2021, we celebrated the centenary of a famous article published in the magazine Zeitschrift für Physik, where the property called spin was discovered and described. Physicists Otto Stern and Walter Gerlach carried out an experiment to confirm the hypothesis of spatial quantization of atoms proposed by Arnold Sommerfeld. In this experiment, silver atoms were collimated by a slit and passed between the poles of an electromagnet, whose magnetic field was not uniform. The result produced in a detector a split line in the shape of a half-open lip, as shown in figure 3 of the article. The original publications on the experiment are four: the first, from 1921, is authored only by Otto Stern, where he proposes to carry out the experiment. The next three, co-authored with Walther Gerlach, aimed to describe the experimental results obtained: one in 1921, and the other two in 1922. Thus, this year 2021 marks the centenary of this important discovery.**

Key words: **Spin, Stern, Gerlach, and quantization**.

I. BRIEF BIOGRAPHY OF STERN AND GERLACH

OTTO STERN (1) was born in Sohrau, now Zory in Poland, Upper Silesia, Germany, on February 17, 1888 and died in Berkeley, USA, on August 7, 1969. He was the son of Oskar Stern, owner of a factory in Breslau and Eugenia Rosenthal. Otto Stern had a brother, Kurt, who became a notable botanist in Frankfurt, and three sisters. In 1892, he moved with his parents to Breslau, where he attended high school. He began to study physic chemistry in 1906, receiving his Ph.D. degree from the University of Breslau in 1912.In the same year, he joined Einstein at the University of Prague and later followed him to the University of Zurich, where he became the Privatdocent of Physical Chemistry at Eidgenössische Technische Hochschule in 1913. In 1914, he went to the University of Frankfurt am Main as private docent of Physical Theory, remaining there until 1921, except for a period of military service. From 1921 to 1922, he was Associate Professor of Theoretical Physics at the University of Rostock, becoming, in 1923, Professor of Physical Chemistry and Director of the laboratory at the University of Hamburg, where he remained until 1933. That year, he moved to the United United, being appointed Research Physics Professor at the Carnegie Institute of Technology, Pittsburgh, where he remained until 1945, becoming professor emeritus. He was responsible for the development and application of the molecular beam method that represents a tool to investigate the properties of molecules, atoms and atomic nuclei. Stern and Gerlach were specialists in deflecting atoms by the action of magnetic fields in their magnetic moment, a branch that earned him the 1943 Nobel Prize in Physics. WALTHER GERLACH (2) was a German physicist who co-discovered the quantization of spin in a magnetic field, the Stern-Gerlach effect. He was born in Munich, Germany, on August 1, 1889 and died on August 10, 1979. He was the son of Valentin Gerlach and Marie Niederhaeuser. He studied at the University of Tübingen and received his doctorate in 1912, under the guidance of Friedrich Paschen. The subject of his dissertation was on radiation measurement. After obtaining his doctorate, he continued as an assistant Paschen, which he had been since 1911. Gerlach completed his qualification in Tübingen in 1916, while serving during the First World War. In 1920, he became a teaching assistant and professor at the Johann Wolfgang Goethe University in Frankfurt. The following year, Gerlach and Otto Stern made a scientific discovery known as the Stern-Gerlach effect. In 1925, Gerlach became an ordinary professor at the University of Tübingen, successor to Friedrich Paschen. In 1929, he started teaching at the Ludwig Maximilians University in Munich, in the vacancy left by Wilhelm Wien. From 1937 to 1945, Gerlach was an influential member of the supervisory team of the Kaiser-Wilhelm-Gesellschaft (KWG) organization, which maintains the Kaiser Wilhelm Institutes (in German: Kaiser-Wilhelm-Institute - KWI), renowned research institutions that organized the basic research in Germany. Kurt Diebner, Abraham Esau, Walther Gerlach, and Erich Schumann were very influential physicists and were related to a nuclear power project in Germany during World War II. For this reason Gerlach was recruited by the British and American Armed Forces under investigation of Operation Alsos, in the development of atomic weapons. From 1948, he became a professor of experimental physics and director of the physics department and then dean of the University of Munich, until 1957. After that he retired and died in 1979.

II. INTRODUCTION

As indicated by GOMES and PETROCOLA (3), the concept of spin is taught for the first time in high school chemistry, when studying the electronic distribution in atoms. For those who follow university courses in the areas of "experimental sciences and engineering", this concept reappears at the end of the basic cycle in the so-called introduction to Modern Physics. For these students, and even for most of the teachers of these courses, the simple mention of this concept is reminiscent of the experience that supposedly "proved" the existence of the electron spin, the Stern-Gerlach (SG) experiment: proposed by the German physicist Otto Stern in 1921 and carried out together with another German physicist, Walther Gerlach, between 1921 and 1922. An example of the importance of this experiment in the development of quantum theory in the 20th century can be found in a renowned quantum mechanics textbook, very popular among students and teachers used in both undergraduate and graduate courses in physics (GOMES and PETROCOLA[3]). The Stern-Gerlach experiment, carried out in 1921, is introduced in the basic manuals of quantum mechanics, in order to illustrate the existence of a particle spin. It had a profound effect on the scientific community at the beginning of the 20th century, being seen as a significant demonstration of the need for a radical abandonment of the concepts of classical mechanics. The basic postulates of quantum mechanics are often formulated in axiomatic ways from the Stern-Gerlach experiment. Stern and Gerlach measured the possible values of the magnetic dipole moments for the silver atoms by sending a beam of these atoms through a non-uniform magnetic field. The classic prediction is that the beam deflected through the magnetic field will spread to a continuous band, corresponding to a continuous distribution of the magnetic dipole moment. However, it was also predicted and proved by the following experiment that the atoms would not follow the classic description. The prediction of quantum mechanics is that the deflected beam would split into several discrete components. The Stern-Gerlach experiment is an example that helps to crystallize the meaning of quantum mechanics. Despite its historical importance and its widespread use as an experimental paradigm for discussing the concept of measurement in quantum mechanics, the authors were unable to display a complete or even particular solution to the problem, that is, the analytical wave of the function particles and their evolution in the time, as well as your self-energies. Several textbooks on quantum mechanics introduce the subject by dedicating a chapter to the experiment with the intention of attuning the reader to the thinking of quantum mechanics (BULNES and OLIVEIRA [4])

III. WHAT IS SPIN?

TAVEL [5] says that when certain elementary particles move through a magnetic field, they are deflected in a way that suggests that they have the properties of small magnets. In the classical world, a charged and rotating object has magnetic properties very similar to those exhibited by these elementary particles. In 1921, Otto Stern and Walther Gerlach, from the University of Hamburg, Germany, conducted a series of important experiments with atomic beams. Knowing that all moving charges produce magnetic fields, they proposed to measure the magnetic fields produced by electrons that orbit nuclei in atoms. To their surprise, however, the two physicists found that the electrons themselves act as if they are spinning very quickly, producing tiny magnetic fields independent of those of their orbital movements. Soon the term 'spin' was used to describe this apparent rotation of subatomic particles. Unfortunately, this analogy is broken, and we have come to the conclusion that it is misleading to evoke an image of the electron as a small rotating object. Instead, we learn to simply accept the observed fact that the electron is deflected by magnetic fields. In fact, the analogy between the spin and a spinning object, certain paradoxes, because, unlike the launch of a ball, for example, the spin of an electron never changes and has only two possible orientations. Furthermore, it is difficult to sustain the very notion that electrons and protons are solid "objects" that can "rotate" in space, given what we know about the rules of quantum mechanics. The term "rotation", however, still remains in many textbooks. But in reality, Spin is a bizarre physical quantity. It is analogous to the rotation of a particle in that it provides an angular momentum for it and a tiny magnetic field called a magnetic moment. In addition, the spin is quantized, which means that only certain discrete rotations are allowed. This situation creates[5] all kinds of complications that make spin one of the most challenging aspects of quantum mechanics. In a broader sense, with regard to the theory of molecular orbital, spin is an essential property that influences the order of electrons and nuclei in atoms and molecules, giving great significance in solid-state physics. Spin is also an essential consideration in all interactions between subatomic particles, whether in high energy particle beams, low temperature fluids or in the fine flow of particles from the sun known as the solar wind. In fact, many processes, if not most physical processes, ranging from the smallest nuclear scales to the largest astrophysical distances, depend heavily on the interactions of subatomic particles and the turns of these particles. Spin is the total angular momentum, or intrinsic angular momentum, of a body. Spin served as a prototype for other even more abstract notions that seem to have the mathematical properties of angular momentum, but do not have a simple classic analog. For example, isotopic spin is used in nuclear physics to represent the two states of a 'nucleus', the proton and the neutron. Likewise, quarks are paired as spin 'up' and 'down', which the names are given to the two quarks that make up common matter. The rotational symmetry of space and time is generalized to include symmetries in more abstract "internal" dimensions, with the result that much of the complex structure of the microworld can be seen as a result of breaking symmetry, connecting deeply to ideas that describe the spontaneous formation of structure in the macroscopic world.

IV. THE STERN-GERLACH EXPERIENCE

The Stern-Gerlach (SG) experiment [5] was originally proposed to test whether the angular momentum of neutral atoms was quantized or not, in the presence of an external magnetic field. With this in mind, Otto Stern proposed the experiment, which had the advantage of not involving any spectroscopic measurements. And as he believed in the theory, the expected result was that the beam of atoms would split into two components when crossing an external magnetic field. However, later, in 1927, it was demonstrated that the magnetic moment measured by Stern and Gerlach was, in fact, the angular momentum of the electron spin. Spin is the intrinsic magnetic moment of particles, and, strictly speaking, there seems to be no classic analog for this fundamental property, even today. The Stern-Gerlach apparatus consists essentially of a magnet producing a non-uniform magnetic field. A beam of atoms penetrates the magnet in a direction perpendicular to the gradient of the magnetic field. As a result of the interaction of their spin with the magnetic field, the atoms undergo a deflection as they pass through the field. At the exit of the magnet, the atoms are detected by counters, which can eventually act as filters. The SG experiment consists of making a beam of atoms (originally silver atoms) pass through a non-homogeneous magnetic field produced by a magnet, and analyze the deposition of these atoms in a collecting plate at the exit of the magnet. Interestingly, it is observed that approximately half of the atoms are deposited at one end of the plate and the other half in the symmetrically opposite position, with virtually no atom being registered in any intermediate position. it is quite strange and difficult to explain. At the time of the experiment, in the 1920s, quantum theory was at an early stage, in a period that today we call "old quantum mechanics", where the most sophisticated was Bohr's atomic model, perfected by Sommerfeld, but which still lacked "good" experimental evidence. It is precisely behind evidence that Otto Stern was in 1921, when he proposed the experiment that we are dealing with in this work.

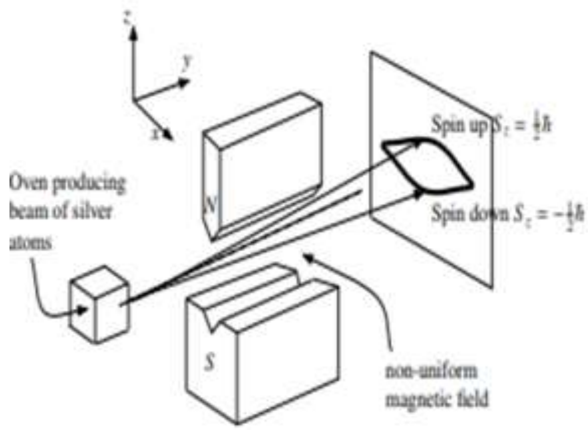
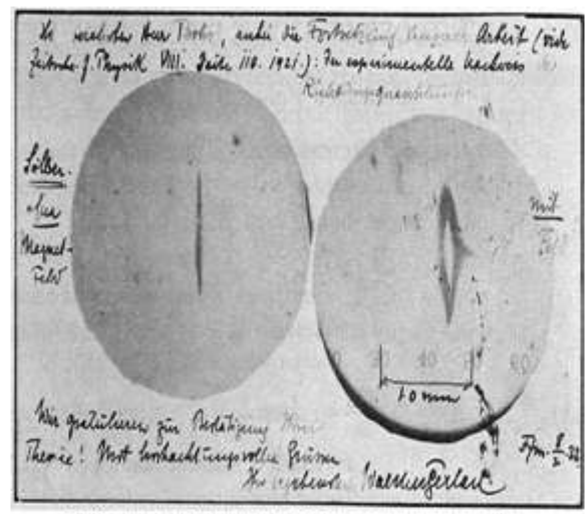


Figure 1 – The Stern-Gerlach apparatus
Source:http://dept.physics.upenn.edu/~pcn/Course/250/Week.of.03.14/sternGerlach.jpg



Gerlach's postcard, dated 8 February 1922, to Niels Bohr. It shows a photograph of the beam splitting, with the message, in translation: "Attached [is] the experimental proof of directional quantization. We congratulate [you] on the confirmation of your theory." (Physics Today December 2003)

Figure 2- Experimental result
Source:
http://dept.physics.upenn.edu/~pcn/Course/250/Week.of.03.14/sternGerlach.jpg

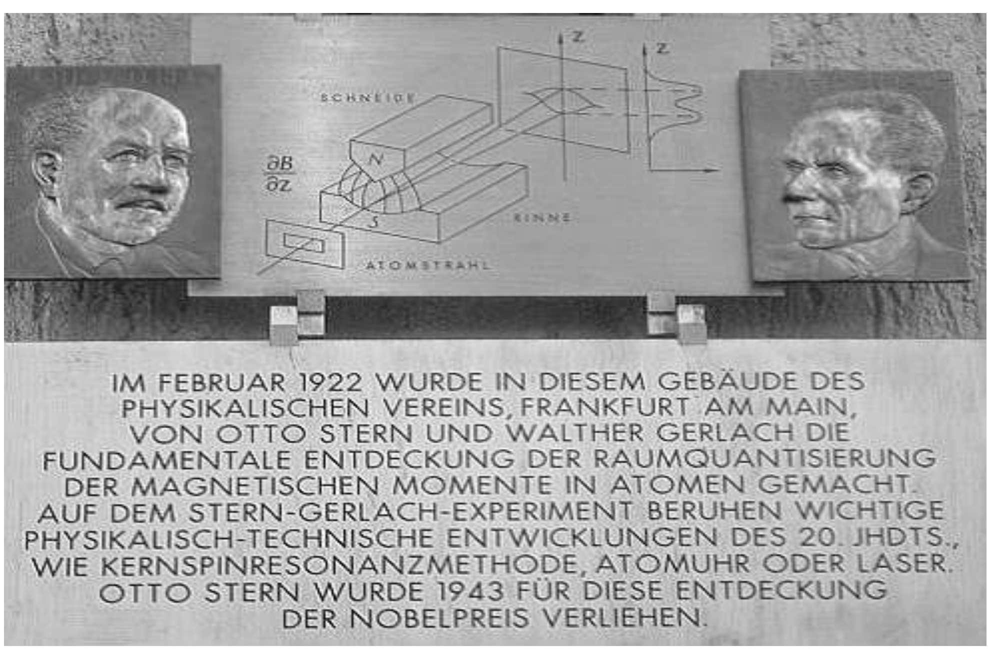


Figure 3: Commemorative plaque referring to the discovery of Spin
Source: http://dept.physics.upenn.edu/~pcn/Course/250/Week.of.03.14/sternGerlach.jpg

V. SPINTRONICS

NIKOLIC [6] explains that Spintronics is a field of electronics that is concerned with the detection and manipulation of electronic spin in solid state physics. This differs from fundamental electronics, since, in addition to the electron charge, its spin is taken into account and exploited as an additional degree of freedom, with possible effects to increase the efficiency of data storage and transfer. Spintronics, also known as Spineletronics or Tronicflow, is a fundamental application in quantum computing. Spintronics helped to create a prototype device used in the industry as a read head and a memory storage cell. It is a sandwich structure called Giant Magnetorestence (GMR) that consists of alternating layers of ferromagnetic and non-magnetic metal. Depending on the relative orientation of the magnetizations in the magnetic layers, the resistance of the device changes from small (parallel magnetization) to large (anti-parallel magnetization). This change in resistance (also called magnetoresistance) is used to change the direction of rotation in electromagnetic fields identified as a magnetic field, which has one of two positions, one up and one down. This provides two extra binary states to the conventional high and low logic values, represented by simple currents. When the rotation state is added to the mix, a bit can have four possible states, which can be called high-high, low-low, low-high and low-low. These four states represent quantum bits or qubits. Some materials have a much higher magneto-resistance, which has come to be called Giant Magneto-Resistance or GMR. The discovery of giant magnetoresistance excited the computer industry, which lives by reading very small magnetic fields on hard or floppy disks. Thus, after this discovery a new technology[6] has grown in recent years: the so-called active heads, almost always based on the phenomenon of magnetoresistance. In addition to advances in technology related to magnetic reading and recording, a new field has emerged in recent years and promises to revolutionize the concept of data storage and reading on the computer. Spintronics is already part of our daily lives, hidden in various devices, especially for data storage, an area in great expansion. Spintronics can be applied in the development of new devices that could consume less electricity and be more powerful for certain types of computational applications compared to conventional devices based on electron charge (KNOBEL[7]).

VI. FINAL CONSIDERATIONS

In general, the concept of spin appears in the school universe in the discipline of chemistry in high school, when studying the electronic distribution in atoms. But it is in basic university education that spin is studied a little more deeply. for those who follow university courses in the areas of "experimental sciences and engineering", this concept reappears at the end of the basic cycle in the study, commonly called "introduction to modern physics". for the students who arrive there, and even for most of the teachers of these courses, this concept is associated with an experience that supposedly "proved" its existence: the Stern-Gerlach experiment. Examples of textbooks widely used in basic university courses are the books by HALLIDAY [8], TIPLER [9], SERWAY [10], and NUSSENZVEIG [11]. Initially, we highlight the chronological options adopted by the authors when presenting the SG experiment. With the exception of the book by HALLIDAY [8], the SG experiment is introduced later to the concept of intrinsic magnetic moment, i.e., the electron spin. This last book, by the way, is what does the best, in the sense of the most faithful to the historical facts, treatment of theme among the analyzed books. We will divide the analysis by separating the books that adopt and do not adopt the chronological sequence between experiments and "spin presentation". In the book by SERWAY [10], the concept of spatial quantization is introduced in section when discussing the orbital angular momentum. The spin is presented a section before. We encountered some problems in the presentation of the Stern-Gerlach experience.

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