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Study of spin 1/2 high school through the Stern-Gerlach experiment

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Abstract: *The study of spin 1/2 through the Stern-Gerlach experiment is one of the parts of a work developed in the classroom with students of the 3rd year of high school. The work begins with the theoretical discussion based on the concept of spin, some aspects about the projections and consolidating the discussion with the Stern-Gerlach experiment. We used the experiment in the virtual form of the precession of spin 1/2, highlighting its importance to complement the initial discussion in an applied way. In general, the approach was based on project proposals, making the students, who are now called student-researchers, develop the ability to develop research work and a sense of belonging in the educational process. We conclude this work by presenting the analysis and discussion of the results and emphasizing the salutary way, whenever possible, for the teacher to approach work that involves projects and distributes in the division of groups to aim at success in the teaching-learning relationship.*

Keywords—spin; Stern-Gerlach; Particles; student-researcher.

1. INTRODUCTION

We know that, in general, schools must comply with the curricular calendar and this article aims to present the possibility of using frontier topics, subjects still under development by research, seeking a greater motivation to students with Physics, making them feel belonging in the educational process. This article presents part of a work carried out with a high school class on the study of spin 1/2, highlighting in particular the Stern-Gerlach experiment.

The involvement in the teaching-learning process was due to the proposal of conditioning the students as researchers, calling them "student-researcher", obviously at the high school level, as a kind of scientific initiation, but in a certain way introducing themes of Modern and Contemporary Physics, where it becomes challenging for both the teacher and the student in this type of approach.

The idea of this project is in line with Moreira [1], where it is sought to develop experimental activities, scientific skills, meaningful learning, dialogicity and criticality, with the involvement of research projects in the classroom.

We will present the structure of this work commenting on the theoretical foundation of the discussions in the classroom in an expository way and raising arguments with the concept of spin, projections and Stern-Gerlach experiment in the first-class meeting.

In the second meeting, we divided two groups, but individually, the student-researchers were able to carry out the virtual experiment of the precession of spin 1/2, showing through the methodology, the way it was applied and what should be worked with the questions imposed by the experimental apparatus.

Finally, we will present the analysis and discussion of the results, graphically showing how the student-researchers operated with the system determined by the professor.

2. THEORETICAL DISCUSSION

2.1 Spin Concept

Spin is a vector quantity that has modulus, direction, and direction, being an intrinsic quantum property of elementary particles, such as mass and charge. Most particles, such as protons, electrons, among others, have spin, however, it cannot present any values for the modulus of the spin of the particles, because it is a quantized quantity and therefore, there is no analogy for classical physics. Spin is a kind of orientation of the particle when immersed in a magnetic field.

Although the word spin means to be rotating, we cannot configure this meaning for the particles of the quantum world, due to the undefined size of these particles [2].

According to Paul Dirac (1902-1984), the discussion of electron spin arose in 1929, but was already experimentally verified by Stern and Gerlach in 1922, where the existence of spin and orbital angular momentum are originated through the magnetism of materials [3].

Feynman (1918-1988) approached the treatment considering that when we place our hand compressing the table, exerting a force on the hand, we will be realizing the existence of spin. We will have the normal force, being the result of the contact with the table, the result of the direction of the spin.

By this we also understand the impenetrability of matter because we cannot get our hand through the table, we will not be able to penetrate the table. This is due to the repulsion of the atoms from the hand and the table, i.e. typically the spin of the electrons.

A form of matter magnetism, we see the case of magnets that have the north and south poles, attracting or repelling, depending on the polarity, all this resulting from spin, because the magnet is a ferromagnetic material and within it, the spins are oriented in a certain direction.

The responsibility for the stability of the phenomena is given by spin, where we observe for example in the gravitational effect of the Earth, constantly attracting the atoms to the center and the force of the spin atoms, manages to avoid gravitational collapse [4].

2.2 The Projections of Spin

The orientation of the particle is given by the spin, being oriented either up or down. The spin is related to the reduced Planck constant, and is then naturally quantized and in the case of the electron, for example, the components of the electron spin can assume two values:

$$S_z = \pm \frac{\hbar}{2} \quad (1)$$

Where S_z, represents the projection of the spin on the z-axis. The spin is what makes the electron a small magnet, with a magnetic dipole moment associated with the spin, because each electron generates a magnetic field [5].

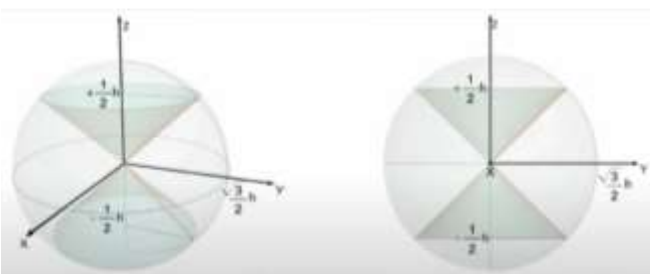

Fig 1. Electron spin projection [5].

Spin is called spin up when it has a positive sign and when it has a negative sign, it is called a spin down [2].

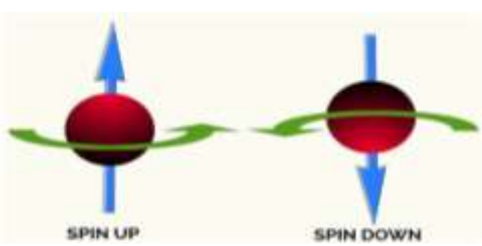

Fig 2. Possible directions for spin: spin up and spin down [2].

There is a quantization of the electron's own motion around the nucleus, the energy being determined by the distance from the orbit to the nucleus and these distances are quantized. The inclination of the orbit is considered, because by classical physics, yes, any inclination would be possible, but in the quantum world, there are permissible inclinations for the orbit of the electron [6].

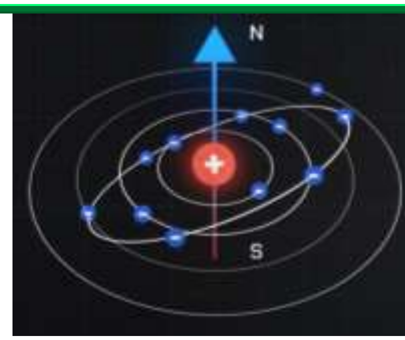

Fig 3. Inclination in the orbit of the electron in the atom [6].

Starting from the horizontal axis, being 0º of inclination, for the electron, we have only 45º of inclination up and 45º of inclination downwards.

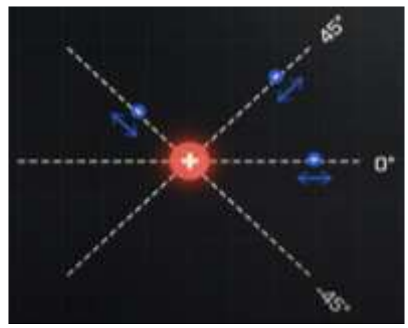

Fig 4. Possible inclinations of the orbit of the electron in the atom [6].

2.3 The Stern and Gerlach Experiment

Regarding the orbits of the electron, which is probability density in the quantum regime, the behavior of the electron orbits is given by the experiment proposed by Otto Stern (1888-1969) and executed by Walther Gerlach (1888-1979).

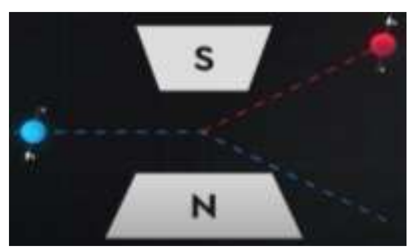

Fig 5. Stern-Gerlach experiment [6].

In the case of the electron, the quantum number of the spin is s = 1/2. So, when observing a magnetic field, the northerly direction of the field is s = +1/2 e o sentido Sul do campo é s = -1/2, respecting the possible inclination of the electron. That's why it's also known as magnetic quantum number [7].

The goal of the Stern–Gerlach experiment is to launch several atoms through a non-uniform magnetic field, generated by two electron magnets, which would deflect the atoms according to the direction of the magnetic field. For every possible direction, it would deflect the atom and if the inclination of the orbit was not quantized, the result would be a continuous smear. But the result was two separate stains. As the atom that was being used in the experiment was the Silver (Ag) atom, where the electromagnetic field of this atom was determined by a single electron in the orbit farthest from the nucleus, that is, this single electron was responsible for the two spots.

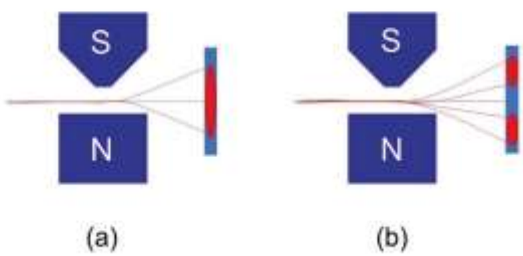

Fig 6. Stern-Gerlach experiment. a) magnetic field off, b) magnetic field on [3].

A relationship between the magnetic field and spin is observed, where the particle of mass *M* and charge *q*, describes a circular motion and has a magnetic moment μ proportional to the angular moment *L*, in the form

$$\mu = \frac{q}{2M} L \tag{2}$$

Where atomic orbits are more stable when there are two electrons, one with spin up and the other with spin down. We won't be able to get atoms with a pair of spin up electrons, that is, two up, or two down, which we won't be able to put three electrons together either. This rule is obeyed by the so-called Pauli Exclusion Principle [6].

The Pauli Exclusion Principle states that in an atom, two electrons cannot exist in the same quantum state [7]. The numbers of the spins will depend on which particle it is and according to the Standard Model, particles are classified into fermions and bosons. The Standard Model is the study of the physics of elementary particles and deals with the entire structure of these particles. In the case of fermions, we have semi-integer spins, for example, s = $\pm\frac{1}{2}, \pm\frac{3}{2}, \pm\frac{5}{2}$ and so on. In the case of the electron, the spin is s = $\pm\frac{1}{2}$.

In the case of bosons, spins are whole numbers. For example, the nucleus of the helium atom always has zero spin, that is, it has no magnetic field. In the case of the Z boson, it has a total spin of 1, with three possible values, -1, 0 and 1. Spin 1, the north of the particle points upwards, spin -1, the north of the particle points downwards and with zero spin, we have no magnetic field, for example in the case of the particle called the Higgs boson.

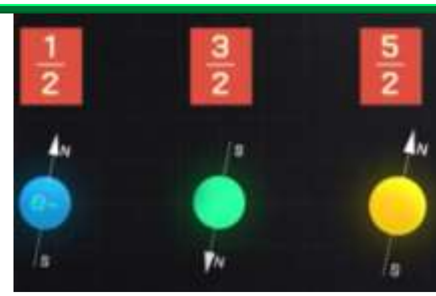

Fig 7. Spin of some fermions [6].

Bosons do not behave like fermions and therefore do not obey the Pauli Exclusion Principle [6].

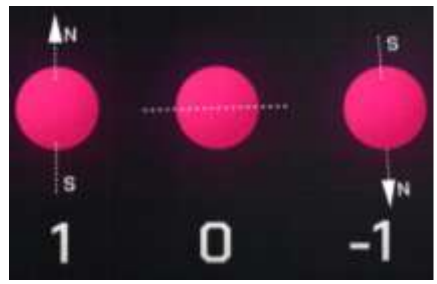

Fig 8. Spin of some bosons [6].

3. Method

The study of spin 1/2 was initially based on a theoretical discussion of the subject, addressing the main aspects of the theoretical foundation in the first meeting and in the second meeting the treatment of the Stern-Gerlach experiment (SGA), where the students made several launches of atoms in a non-uniform magnetic field, through the electromagnets, demonstrating the agreement of the deviation with the direction of the positive or negative spin. The simulation was applied to a class of 23 high school students from a school in São Cristóvão, Rio de Janeiro, Brazil [8].

We used the virtual experiment through a website at St Andrews Amrita University in Fife, Scotland. The purpose of this site is to work with quantum mechanics topics at various levels, in English and German languages [9].

There are several experiments on the site, but for the purpose of this work, we applied the 1/2 spin precession. We made a division with two groups with 12 students in the Alpha group and 11 students in the Beta group. The students, in the condition of student-researcher, in their respective groups, developed their work, being supervised by the teacher to achieve the objective foreseen by the challenges.

Each student-researcher performed the experimental measurements and their data were consolidated within their group. In all the challenges, the student-researchers only needed to perform the operation of the magnetic field angulation, which by the apparatus goes from 0º to 360º, with a measurement step of 45º to 45º, and the angulation of the EMS (Stern-Gerlach apparatus) that goes from 0º to 90º, with a 22.5º step of measurement variation.

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3.1 Procedure

Spin precession is the probability of measuring a given spin component at a given time and, in this simulation, we send spin 1/2 particles through two Stern-Gerlach devices (SGAs), which consists of a magnetic field aligned to a certain axis. The particles separate into two discrete flows, one with a spin-up component and one with a spin-down component along this axis (x-axis, or z-axis).$\hbar/2 - \hbar/2$

The particles pass through two subsequent SGAs that can be rotated together. All particles that pass through the first (**SGA 1**), pass through the second (**SGA 2**) with the same deflection.

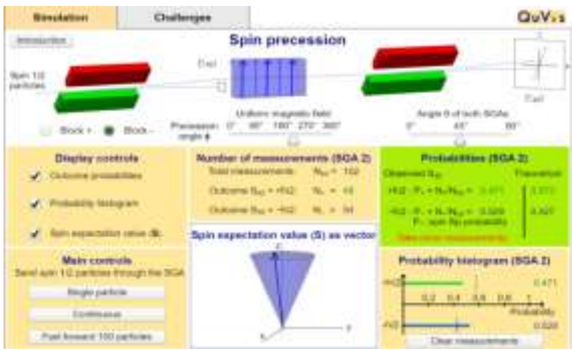


Fig 9. Virtual Spin 1/2 Precession Experiment [9].

To start the simulation, the student-researcher must click on **controls to** send particles, being able to modify the angle of the magnetic field and the SGAs.

In the left column, we have the (**Block +**) and (**Block -**) "blocks" icons. That means that's where we're going to detect the particle higher or lower than the x- or z-axis. You can see that the coordinate frame is on the right side of the (**SGA 2**). You can choose either Block + or -, make the angular change of the magnetic field from **0º to 360º** and the angles of the SGAs from **0º to 90º**.

Below the Block icons, we have the **main controls**, where you can send by clicking on a single particle, a continuous beam of particles, or every 100 particles.

In the central column we have the **number of measurements (SGA 2),** showing the total measurements and the result of each axis of the spin (+) or spin (-) of the x or z direction, depending on the configuration.

Below the item number of measurements (SGA 2), we have the **expected value of spin (S) as a vector**, where it shows the projection of the spin on the three-dimensional coordinate (x, y, z).

In the rightmost column, we have the item **probabilities (SGA 2),** which shows the theoretical observation of the configuration adjusted for a given axis.

And finally, below the probabilities item (SGA 2), we have the **probability histogram (SGA 2),** showing the graph of the spin (+) or (-) with its probability. On this same panel we have the button (**clear measurements**) to delete all measurements and make a new measurement.

In the challenges item, the student-researcher should research, through the measures of the experiment and identify, showing the results obtained to the teacher in a correct way, the following activity proposals:

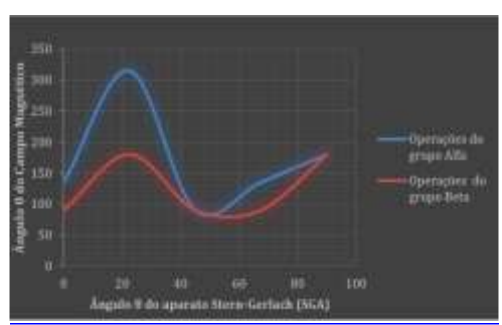
1. What is the angle of the magnetic field and the angle of the SGAs in which Only the particles deflected in the + x direction pass through SGA 1 and all particles are deflected in the – x direction after passing through SGA?
2. What is the angle of the magnetic field and the angle of the SGAs that only particles deflected in the + x direction pass through SGA 1 and on average, half of the particles are deflected in the + and – x directions after passing through SGA 2?
3. What is the angle of the magnetic field and the angle of the SGAs at which Only particles deflected in the direction θ = + 45º, pass through SGA 1 and as many particles as possible are deflected in the direction – 45º, after passing through SGA 2?

   após passarem pela SGA 2?
4. What is the angle of SGA 1, can we make all particles passing through the SGAs change from a spin-up to spin-down eigenstate given the magnetic field aligned with the z axis?
   (A) 15º (B) 22,5º (C) 45º (D) 67,5º (E) 90º

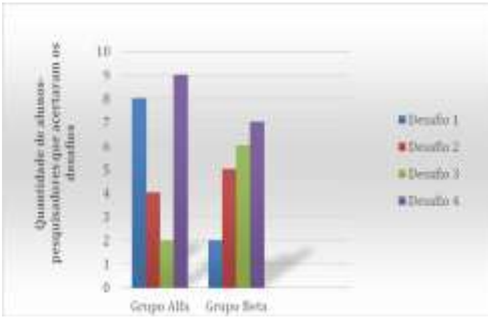
4. Results and Discussion

The approach to this study project on spin 1/2 is so that the student-researcher thinks about all the activities exposed. The student-researchers performed the 1/2 spin precession experiment and analyzing the data in the following graph, we noticed that the Alpha group identified by the blue line and the Beta group by the red line, had similar trends in the operations of the angle θ of the (SGA) to 45º and 90º, which seems to be more familiar to the operation for these angles.

The graph shows the tendencies that each group has in the operations of the magnetic field angles and the Stern-Gerlach apparatus (SGA). The realization of this graph was through the collection of data from each student-researcher in their operations, where they placed it in a spreadsheet and sent it to the teacher and took an average of the actions for the group [8].



Grap 1. Operations of the student-researchers of the virtual experiment on the precession of spin 1/2 of the Alpha and Beta groups in relation to the angles of the magnetic field and the Stern-Gerlach apparatus [8].



Grap 2. Number of student-researchers who got the challenges right within the Alpha and Beta groups, in the operations of the virtual experiment on the precession of spin 1/2 [8].

5. Final considerations

We noticed a motivation on the part of the student-researchers after the work carried out, because although initially the project started in a theoretical way and in the expository format, there was involvement of the teacher with the students, raising questions, seeking greater knowledge about the theme treated.

Whenever possible, it is important for teachers to place students as protagonists of their own knowledge, because many years ago the educational system placed students in a passive posture, without the possibility of questioning or developing projects.

The virtual experimental application of the Stern-Gerlach experiment went beyond showing its applicability to the study of spin, but also to develop in students this ability to work with projects, having a sense of belonging in their own construction of knowledge.

Groups are important for students to have this relationship with each other, discussing, exchanging ideas, strengthening each one's educational process.

It is indeed challenging to use these topics of modern and contemporary physics, but it is salutary for the educational process as a whole.

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