Quantisation of angular momenta in atoms

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Abstract. The aim of the work was to see if the direction of angular momenta in atoms is quantised. In order to do it, a beam of atoms is split, and deflected because of interactions between atomic dipole moments and an externally applied magnetic field. In which case, the angular momenta in atoms is definitively quantised. Firstly, the detector was checked and then the operation of the detector was characterised; secondly, the beam was detected and characterised with residual magnetisation minimised; thirdly, the beam was detected and characterised with magnetic field present. The sample used to determine the magnetic moment was Potassium. The Bohr’s magneton constant value was found to be (9.22±0.7)*10⁻²⁴ J/T. The answer is lower than the nominal value but lies within the expected error range. This proved the accuracy of the work done and proved the quantisation of the angular momentum, since it proved the presence of magnetic moment.

1. Introduction

The experiment was carried out to see the deflection of a beam of neutral atoms in potassium. The experiment was done in an inhomogeneous magnetic field, so that the deflection would be done solely by nuclear magnetic moments. If the moments were quantised then the beam would split into two beams, corresponding to parallel and anti-parallel alignments of magnetic moments [1].

The magnetic dipole momentum of an atom, µ, is given by the following expression µ=-gL µB l/ħ - gs µB S/ħ, where: L-the total orbital angular momentum of electrons in the atom, S is the total spin (gL = 1; gs ≈ 2; µB = 9.274×10⁶78 J / T) [2].

The experiment allows to study the spins of particles by measuring how a beam is deflected when it passes an area of inhomogeneous magnetic field (figure 1).
There were some challenges to overcome for the experiment to turn out successful. First of all, it was the controllable high vacuum to be attained, so that the beam is facing as small resistance as possible in order to reduce the scattering. Secondly, it was to find the detector with good enough efficiency for better statistics. Finally, it was to find a material that has a relatively low vaporization temperature.

As for the last problem, the chosen material was potassium. The structure of Potassium is such that the total orbital momentum of electrons is zero, \( L = 0 \). But because it has a single unpaired valence electron, its atom has a net spin and hence dipole momentum. The experiment should allow us to measure the strength of the intrinsic spin dipole moment, and thus to measure the Bohr’s magneton, \( \mu_B \) [2].

The second problem to overcome, was dealt with using a Langmuir-Taylor detector. The detector has the internal properties of the detector such as resolution and efficiency of appropriate values for the experiment. As for the first problem, the vacuum was created using a controllable vacuum pump, that would limit the maximum and minimum range of vacuum within a certain range. The range was from a few \( 10^{-4} \) hPa to a few \( 10^{-6} \) hPa.

Just as challenging was the investigation of the spatial quantisation of spin. When in classical physics the direction and magnitude of angular momentum vector can take any value, in quantum mechanics, angular momentum and spin are quantised.

The spin of a particle is shown by two quantum numbers, \( S \) and \( m_z \). These determine the magnitude and \( z \)-component of the spin: \( S^2 = S(S + 1) \hbar^2 \) and \( S_z = m_s \hbar \).

For the interpretation of the measured particle deflections (\( \Delta z \)), we should consider the energy of interaction between a particle with magnetic dipole moment \( \mu \) and an external magnetic field \( B \), which is given by equation \( E = -\mu \cdot B \) [3].

For the experiment we consider a magnetic field with one non-zero component, which is chosen to be in \( z \) direction. Assuming that the force experienced inside the field region by a particle is constant, the deflection of the particle measured at the detector would be \( \Delta z = \frac{\mu_z dB_z}{m} \frac{L}{v^2}(l - \frac{L}{2}) \), here \( m \) is the mass
of the particle, \( v \) is its velocity and \( l \) is the total distance that would be travelled by an undeflected beam between entering the field region and reaching the detector plane.

In the case when the incoming beam originates from a hot furnace (the case in the experiment) the velocities of the particles in the incoming beam varies in range according to Maxwell-Boltzmann distribution. Using the distribution of velocities of particles and specifying the particles with particular values for \( \mu_z \), the shape of this function is given by

\[
\Delta z_p = \frac{\mu_z}{6 kT} \frac{dB}{dz}(l - \frac{L}{2}) \tag{4}
\]

2. Methodology

Firstly, the background noise for the detector was calculated. Using a method of flashing the value for it was found to be 15 pA. Secondly, the apparatus was prepared to do the experiment. The temperature for the furnace was held between 175 °C and 190 °C, and for safety reasons the vacuum pressure was held between \( 10^{-4} \) hPa and \( 10^{-6} \) hPa. After this step, all was left is to characterize the beam with no magnetic field present and with magnetic field included respectively. To ensure that the error influence for the experiment was held to its minimum the residual magnetization was removed by switching the magnetic poles of the magnet and varying the magnet power. Finally, all results were recorded into excel to get the needed graphs.

![Figure 2. The experimental set up [5].](image)

In figure 2 there are 4 power supplies: a) the potassium furnace; b) the magnets; c) the detector voltage; d) the output amplifier.

The 5 output meters: A) the potassium furnace temperature; B) the current supplied to the furnace; C) the current supplied to the magnets; D) the voltage applied across the detector; E) the amplifier output.

3. Results

Due to a single unpaired valence electron, the Potassium atom has a net spin, and thus a magnetic dipole moment. The obtained results verify this theoretical assumption (figure 3 and figure 4), and also verifies
the process of measurement of the strength of the intrinsic spin dipole moment. This is an important verification of the existence of spin and of measurement of the Bohr magneton $\mu_B$.

**Figure 3.** Graphical illustration of the current varying with spindle position, when there is no magnetic field present.

The graphs clearly show that the width of the peak depends on the current. The higher the amplifier current than narrower the beam. This suggests that not only the increase in the strength of the magnetic field would affect the positions of the peaks on the graphs but the spindle position as well.

**Figure 4.** Illustration of current varying with spindle position, when the magnetic field is present, and the magnetic current is varied from 0.3 to 0.9 A, in steps of 0.3 A.
The change in the strength of the magnetic field showed that the width of the peaks changed as well. The higher the magnetic field was, the wider were the peaks. Similarly, the current output was getting lower with the increase in the strength of the magnetic field. The magnetic field used was inhomogeneous, so the existence of two peaks of the beam from figure 4. shows that the angular momenta of the particles is quantized as was mentioned in the introduction section. This means that in the presence of the magnetic field the particles spin gets oriented in one certain position, and change in the axis of the magnetic field influences the passing beam and as a result of spindle rotation we get two peaks, proving that the angular momentum is fixed. Quantisation of angular momenta is only possible according to the quantum theory, when the particles indeed have a fixed spin. Using this information, we determined the corresponding value of Bohr’s Magneton by measuring the position of peaks for the particles in the beam to quantify the magnetic moment caused by the spin angular momenta and got a value of $\mu_B = (9.22\pm0.7)\times10^{-24}$ J/T which was in correspondence with the tabulated values for the constant. This proved the accuracy of the obtained results.

4. Conclusion
To sum up, the experiment was held in order to see the quantized angular momenta of particles. The methodology used to do so was to allow to pass a particle beam from potassium as a source with and without magnetic field present. The results obtained showed that the width of the peaks from the graphs was dependent on the current. The higher the amplification was, the narrower was the peak. The presence of the magnetic field brought new changes to the peaks. With increase in strength of the magnetic field, the peaks became wider, and the current output became smaller. But most importantly two peaks were observed, instead of one compared to the absence of the magnetic field. This proved the quantisation of the angular momenta for the beam particles. The value that proved the concept of quantization of angular momenta, the "magnetic moment" was found to be $\mu_B = (9.22\pm0.7)\times10^{-24}$ J/T.

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