# Zeeman Effect

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**1 author:**

Sondos Suwan
An-Najah National University

# *Zeeman Effect*

Department of Physics, Al-Najah University

Prepared by: Sondos Suwan

Supervise by:Prof. Issam Ashqar

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# *Introduction*

- In physics and astronomy, the splitting of a spectral line into two or more components of slightly different frequency when the light source is placed in a magnetic field.
- It was first observed in 1896 by the Dutch physicist Pieter Zeeman as a broadening of the yellow D-lines of sodium in a flame held between strong magnetic poles.
- It is analogous to the Stark effect, the splitting of a spectral line into several components in the presence of an electric field.

# *History*

- Zeeman's discovery earned him the 1902 Nobel Prize for Physics, which he shared with a former teacher, Hendrik Anton Lorentz, another Dutch physicist. Lorentz, who had earlier developed a theory concerning the effect of magnetism on light.

- This theory was confirmed by Zeeman's research and later modified by quantum mechanics

# *Zeeman Effect*

The atomic energy levels, the transitions between these levels, and the associated spectral lines discussed to this point have implicitly assumed that there are no magnetic fields influencing the atom. If there are magnetic fields present, the atomic energy levels are split into a larger number of levels and the spectral lines are also split. This splitting is called the *Zeeman Effect*.

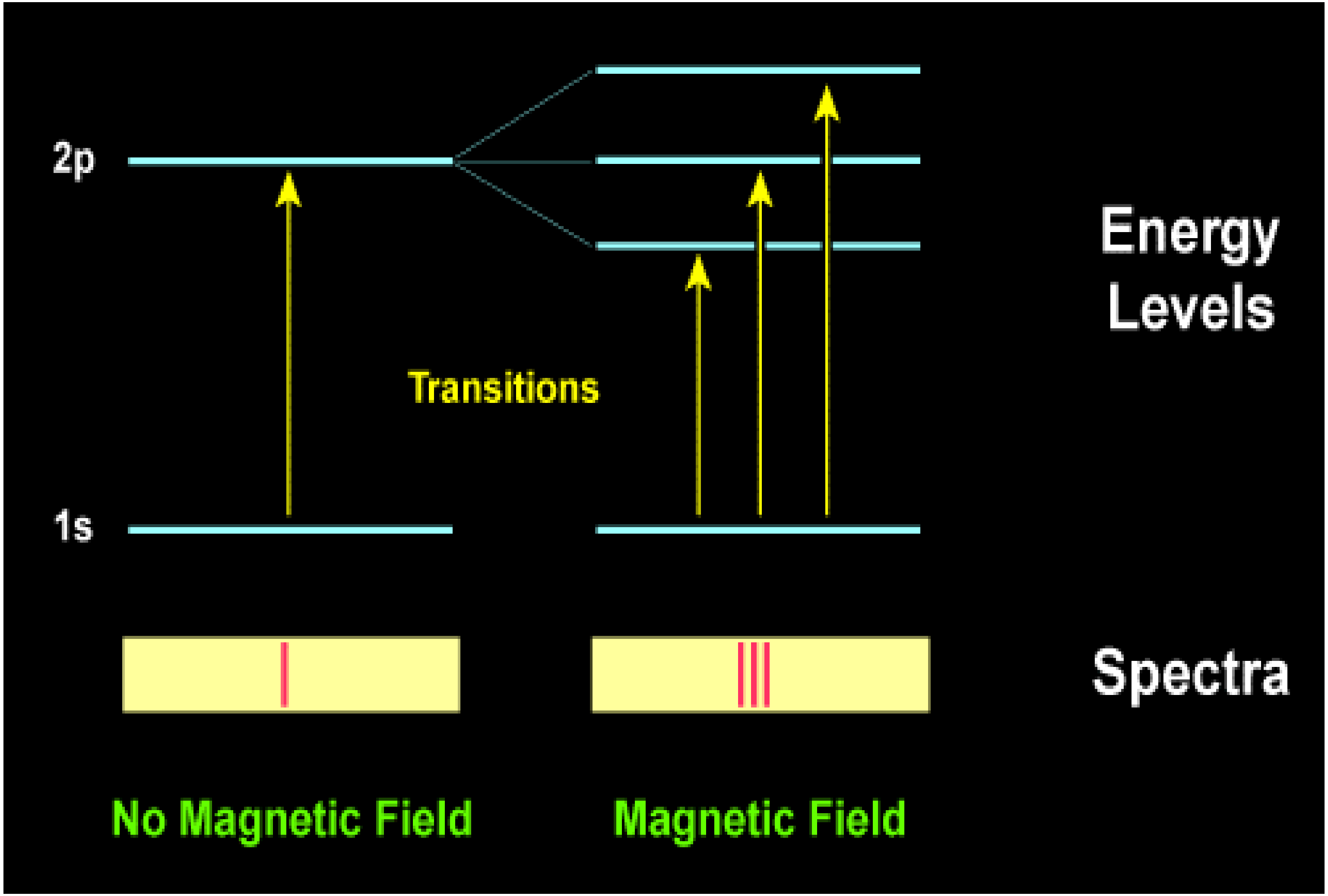
## *Zeeman Effect*

The Zeeman effect describes the splitting of spectral lines in the presence of a magnetic field. In the absence of a magnetic field, emission is observed as a single spectral line and is dependent only on the principal quantum numbers of the initial and final states. In the presence of an external magnetic field, the principal quantum number of each state is split into different substates, resulting in permitted transitions that have frequencies above and below the transition that results in the absence of a magnetic field. The degree of the splitting depends on the field strength.

# *Zeeman Spectral Splitting*

The pattern and amount of splitting are a signature that a magnetic field is present, and of its strength. The splitting is associated with what is called the *orbital angular momentum quantum number* L of the atomic level. This quantum number can take non-negative integer values. The number of split levels in the magnetic field is (2 * L + 1).

The following figure illustrates the Zeeman effect:



Atomic physicists use the abbreviation:

"s" for a level with L=0

"p" for L=1

"d" for L=2

and so on (the reasons for these designations are of historical interest only). It is also common to precede this designation with the integer principle quantum number n. Thus, the designation "2p" means a level that has n=2 and L=1.

- The lowest level is an "s" level, so it has L=0 and 2L + 1 = 1, so it isn't split in the magnetic field, while the first excited state has L=1 ("p" level), so it is split into 2L + 1 = 3 levels by the magnetic field. Thus, a single transition is split into 3 transitions by the magnetic field in this example.
- The Zeeman effect can be interpreted in terms of the precession of the orbital angular momentum vector in the magnetic field, similar to the precession of the axis of a spinning top in a gravitational field.

# *Polarization of Spectral Lines*

- The lines corresponding to Zeeman splitting also exhibit *polarization effects*. Polarization has to do with the direction in which the electromagnetic fields are vibrating.
- One practical example in astronomy of such polarization effects is that in the preceding example the middle transition is polarized such that it cannot be easily be observed from directly over a surface perpendicular to the magnetic field
- When looking directly down on a sunspot (which have strong magnetic fields) typically only two of the three transitions shown above can be seen and the line is observed to split into two rather than three lines (the missing transition could be observed from a different angle where its light would not be suppressed by the polarization effect, but it is very weak when observed from directly overhead).

# *Zeeman Effect*

Interaction between atoms and field can be classified into two regimes:

- Weak fields: Zeeman effect, either normal or anomalous.
  - ➢ Normal Zeeman effect agrees with the classical theory of Lorentz.
  - ➢ Anomalous effect depends on electron spin, and is purely quantum mechanical.
- Strong fields: Paschen-Back effect.

# *Weak field*

If the spin-orbit interaction dominates over the effect of the external magnetic field, and are not separately conserved, only the total angular momentum is . The spin and orbital angular momentum vectors can be thought of as processing about the (fixed) total angular momentum vector The (time-)"averaged" spin vector is then the projection $\vec{J}$ the spin onto the direction of

$\vec{J}$:

$$\vec{S}_{\text{avg}} = \frac{(\vec{S} \cdot \vec{J})}{J^2} \vec{J}$$

and for the (time-)"averaged" orbital vector:

$$\vec{L}_{\text{avg}} = \frac{(\vec{L} \cdot \vec{J})}{J^2} \vec{J}.$$

# *Strong field*

The Paschen-Back effect is the splitting of atomic energy levels in the presence of a strong magnetic field. This occurs when an external magnetic field is sufficiently large to disrupt the coupling between orbital ( L ) and spin ( S ) angular momenta This effect is the strong-field limit of the Zeeman effect

When s=0 , the two effects are equivalent. The effect was named after the German physicists Friedrich and Ernst E. A. Back.

$$E_z = \left\langle \psi \middle| H_0 + \frac{B_z \mu_{\rm B}}{\hbar}(L_z + g_s S_z) \middle| \psi \right\rangle = E_0 + B_z \mu_{\rm B}(m_l + g_s m_s)$$

# *Normal Zeeman*

In the Normal Zeeman effect, a singlet line of frequency $v_o$ splits into three plane polarized component lines having frequency $v_o - \Delta v$, $v_o$ and $v_o + \Delta v$, when viewed at right angles to B. The component lines with frequency $v_o \pm dv$ are plane polarized with the electric vector perpendicular to B, while the central line has the same wavelength as the original is also plane polarized but the electric vector in this case is parallel to B

# *Anomalous Zeeman*

The anomalous Zeeman effect is observed due to transition between multiple states. In this effect, the spectral lines _are observed in more than three components after splitting

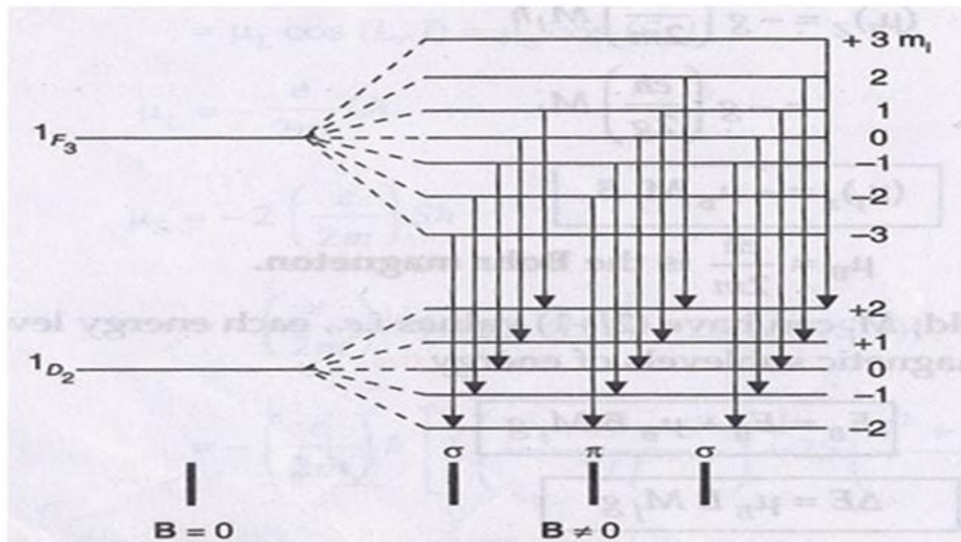



*FIGURE 10.6*

# *G- Factor*

- When the Zeeman effect was observed for hydrogen
- Effects of electron spin were discovered by Goudsmit and Uhlenbeck, they found that the observed spectral features were matched by assigning to the electron spin a magnetic moment, then value of g is

$$g = 2.002319304386$$

# Application

- To measure the magnetic field, e.g. that of the Sun and other stars or in laboratory plasmas .
- In nuclear magnetic resonance spectroscopy, electron spin resonance spectroscopy, magnetic resonance imaging (MRI) and Mossbauer spectroscopy.
- It may also be utilized to improve accuracy in atomic absorption spectroscopy.
- A theory about the magnetic sense of birds assumes that a protein in the retina is changed due to the Zeeman effect .
- Measurement of pulsed magnetic field .
- The Zeeman effect in molecular lines, the asymmetries observed in Stokes profiles from sunspots, and the interpretation of spectro polarimetric observations in the infrared.
- To use the Zeeman effect for increasing the selectivity of laser isotope separation.

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# Thank YOU