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Potassium Vapour Magnetometers – A Short Summary

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Introduction

This paper is intended to provide a short overview for professionals and students who are interested in learning more about potassium magnetometers and their differences from other types of magnetometers available today. Key topics include:

- Physical overview of quantum magnetometers
- Optical pumping of alkali vapours
- Broad line Cesium, Rubidium and Helium versus narrow line Potassium
- Standard and super-resolution K-sensors and systems
- Future directions

This paper is based on more than 10 years of research and development into the topic by GEM Systems, Inc. as well as other published results from the scientific community.

Physical Overview of Quantum Magnetometers

Some subatomic particles, in particular electronic and nuclei of some elements process spin; rotation and they have an accompanying mechanical moment.

$P = I\, h/2\pi$ I = spin number, half integer   h = Plank's constant

Since the particles with spin have charge, they also possess a magnetic moment related to the mechanical by

$\mu = \gamma\ p$ γ = gyromagnetic constant

In an applied magnetic field, such as the Earth's, magnetic moments can only assume discrete orientations governed by the spin number, I. Coupling energy between the particle and the magnetic field is

$E = -\vec{\mu}\ \vec{H} = \mu H \cos\varphi$ this is a scalar product of the two vectors

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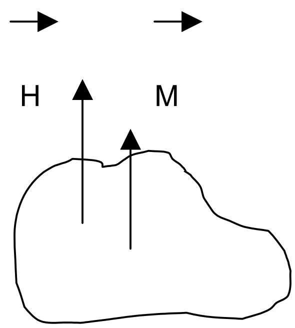
There can be only 2 I + 1 permitted states. For I = ½ for electrons and protons there are only 2 allowed energy states, permitted angles between the two vectors are $\pm 45^{0}$. In an assembly of spins the distribution of populations of the two levels is regulated by

$$e^{-E/kT} = e^{\mu H/kT}$$

so the higher energy level is less populated. The result is a slight paramagnetism of the assembly of particles with spin due to spin and the magnetic moment.



Individual spinning particles precess around the magnetic field with the angular frequency

$$\omega o = \gamma H$$

where γ is a gyromagnetic constant. Since there are many particles spinning incoherently, there is no macroscopic effort of it i.e. the magnetization due to spins appear static.

However, if one applies a rotating magnetic field of the angular frequency ωo in the plane perpendicular to the magnetic field, the vector of magnetization will be deflected off the direction of magnetic field and will precess around it with the same frequency.

Precessing or rotating magnetization will induce a voltage in a coil suitably wound around the assembly of spins. Frequency of the detected voltage is proportional to the applied field to a great precision.

In a weak magnetic field such as Earth's, the induced voltage is far too small for direct detection. Instead various means are applied in order to polarize the sensor spin assembly i.e. to increase the macroscopic magnetization due to spins.

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There are three principally different groups of quantum magnetometers:

- Proton magnetometers use strong DC magnetic fields to increase protons magnetization.
- Overhauser effect is based on a mixture of electrons and protons. Electrons are manipulated to transfer their polarization to protons.
- Some alkali metals and He 3 and 4 can be “optically pumped” to increase the magnetization due to their electron spins.

We will be concerned only with the third group.

Optical Pumping of Alkali Vapours

Only unpaired and free electrons exhibit spin with the features described above. Vapours of the alkali group of elements have a single, unpaired electron in their valence shell and they can be readily used as sources of electrons with spins. Helium gas in the other hand needs to be ionized in order to eliminate one electron from the valance shell; the remaining electron then behaves as an unpaired electron.

In ground state ^{2} S1/2 the electron has 2 energy levels, or –1/2 or +1/2 spins. To polarize it we need to depopulate one level and overpopulate the other. This is done by applying a light beam with special characteristics. Gas discharge lamps of the elements in question are used as sources of polarizing light. Photons of two spectral lines D1 and D2 can lift the electrons from either energy level of the background state into metastable state. There will be very little in polarization if we allow both D1 and D2 to act their polarizations are opposite and we need to eliminate or suppress one. This is done by an interference filter.

Next we need to circularly polarize the D1 light. Then, only electrons with - ½ spin will be able to absorb the quantum of light and be lifted into metastable 2 P1/2. There is a natural decay from metastable levels back into background levels, but eventually the - ½ spin level will be depleted, and the sensor will become more transparent (not absorbing photons any more).

If we now apply rotating magnetic field around the sample and in the plane perpendicular to the applied magnetic field, there will be a precession of the magnetization due to electron spins.

Depending on the phase of this precession the ability of the spins to absorb protons of D1 light will vary i.e. the intensity of light passing through the sample of spins will be modulated in synchronization with the preceding magnetization.

We can detect this modulation; amplify it and measure its frequency and compute the value of the applied magnetic field from it.

In reality, the situation is somewhat different. Due to magnetic properties of the nucleus of the alkali metals, there is a whole mini-spectrum of spectral lines instead of a single one.

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Broad Line Versus Narrow Line Spectra

Potassium and Rubidium have 6 spectral lines of various intensities, Cesium 133 14 and Helium 4 just one but very wide. Width of the spectral line depends on many parameters such as the size of cells, collision of the atoms with the walls of the cells, collision with buffer gas, spin exchange, etc.

Contemporary Cs and Rb magnetometers have wide overlapping spectral lines. A composite spectral line is not symmetrical but the position of its peak depends on the geometry of the sensor and the applied magnetic field. There is a large shift in precession frequency when we change the orientation of the sensor in steady magnetic field.

This weakness is largely corrected by applying a split beam technique that symmetrizes the shape of the strong but wide spectral single line.

Advantaged of the strong single line are:

- Very high tolerance to gradients of magnetic field.
- Simplicity, since the cesium magnetometer can self-oscillate its amplified signal is used to create a rotating magnetic field around the sensor, causing self-oscillations.

Weaknesses are:

- Reduced sensitivity
- Poor absolute accuracy
- Pronounced tilt or heading error.

Potassium spectral lines can be made very narrow and completely separated from each other. Self-oscillation is now not suitable, as it would result in a beating of several individual frequencies. Instead an auxiliary oscillator is used to create rotating field around the sensor for one spectral line only. Signal generated from that operation is then used to frequency lock the auxiliary oscillator's frequency.

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Technically this is more complex than self-oscillations. Advantages are:

- A maximum of the resolution
- Very high absolute accuracy
- "Heading error" due to varying geometry between the sensor axis and the magnetic field is very much reduced.

The disadvantage is also a limited tolerance to gradients – as gradients widen the spectral lines.

The sensors of Potassium magnetometer need to be larger size than Cesium in order to achieve narrow spectral lines. In practice we use 70mm dia cells to achieve about 1nT line width and 120mm cells will give about 0.15nT.

Standard and Super-Resolution K-Sensors and Systems

We have built the observatory like testing site at Georgina Island in the Lake Simcoe, Ontario to test our "supergradiometer". Latest results show about 0.1pTpp noise gradient mode and 1 second measuring interval. This is somewhat more than 10fT rms per channel. Our standard gradiometers are about 5 times less sensitive.

As an illustration of our latest testing of the supergradiometer, enclosed is an anomaly of about 0.4pT registered by the supergradiometer.

Geometrical restrictions of potassium are very similar to those of cesium: right angles and collinear orientation related to the magnetic field directions are forbidden. Whether you define operating angles from 2-88^0 or 10 – 80^0 is really irrelevant – physics of it stays the same.

Future Directions

Current research is aimed at reducing the sensor size thereby reducing sensitivity to gradients while maintaining a relatively high sensitivity in comparison with other commercial instrumentation.

GEM Systems continues to advance its research and development which is leading to the next generation of gradient-tolerant ground systems based on new sensor technology as described above and high sensitivity airborne systems. Airborne systems currently in the air or being developed include high sensitivity single sensor systems as well as and multi-sensor airborne gradiometers.