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# II. Measurement of Weak Magnetic Fields by Optical Pumping Methods

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## A. *D. C. Alkali Vapor Magnetometer.*

In 1950 A. Kastler [1] suggested the use of circularly polarized resonance radiation to orient atoms such as mercury and sodium. This type of orientation was demonstrated in several laboratories by observing the polarization of resonance radiation scattered from a sample which was in the form of an atomic beam or a vapor. H. G. Dehmelt [2] showed in 1957 that a substantial orientation could be produced and detected easily in sodium vapor by having one of the two principal resonance lines considerably stronger than the other and by using a sample containing a pressure of the order of several cm Hg of an inert buffer gas as well as the sodium vapor. Under these conditions the optical absorption coefficient for the sample depends on the degree of orientation of the sample and provides a convenient method of monitoring the degree of orientation. Samples with special wall coatings may also be used, and in some cases give better results than those containings a buffer gas.

Dehmelt's method can be used with any of the alkalis, but in the following discussion only rubidium—87 will be considered since it is commonly used in alkali vapor magnetometers.

In the D.C. rubidium magnetometer [3, 4] light from a rubidium discharge lamp is passed through an interference filter and a circular polarizer, through the rubidium absorption cell, and then to a photodetector. The interference filter passes only the longer wavelength principal resonance line at 7947 Å. The light passes through the sample roughly parallel to the magnetic field and a weak R.F. magnetic field at right angles to the static field is provided. When the applied frequency corresponds to the Zeeman splitting of the rubidium—87 atoms, about 700 kilohertz per gauss, then resonance transitions will take place which change the degree of orientation of the sample and thus the amount of light reaching the photodetector. The magnetic field can be calculated from the observed resonance frequency.

If the Zeeman transitions are studied carefully using a weak R.F. field and low light intensity, then splittings of the resonance line caused by the magnetic moment of the rubidium—87 nucleus will be observed. In a field of 0.5 gauss the spectrum will consist of four components of unequal size about 40 cycles apart and two other weaker components, also 40 cycles apart, about 1.4 kilocycles higher in frequency. The smaller intervals are called second order splittings because they are proportional to the square of the field, while the splitting between the two groups is linearly proportional to the field. The relative intensities of the components depend on the light intensity, orientation, and R.F. level. At higher R.F. levels additional components due to multiple quantum transitions can be observed between the main components of each group.

If 50-60 hertz fields are present the spectrum will be complicated by sidebands at this frequency. The presence of 0,1 to 1 milligauss of 50-60 hertz fields frequently causes enough sidebands so that individual components cannot be resolved and a single broad resonance is observed. Care must thus be taken to avoid power frequency fields.

Under good conditions a linewidth of 15 to 20 hertz (about 20 to 30 microgauss) and a signal-to-noise ratio of about 50 have been obtained in a field of 0.5 gauss using 10 hertz modulation of the field and a phase-sensitive detector with a time constant of one second. The main components are then fairly well resolved, and the strongest can be used to measure the field in terms of the rubidium—87 frequency to an accuracy of about 1 microgauss if the apparatus is sufficiently non-magnetic. Narrower lines can be achieved with reduced signal-to-noise ratio, but the required lower modulation frequency causes practical difficulties. The absolute accuracy achievable is presently limited to about 12 parts per million by uncertainties in the g-factor for rubidium and in the proton gyromagnetic ratio. A direct measurement of the rubidium frequency in a known field is expected to reduce the uncertainty to about 6 parts per million, the same as for the proton gyromagnetic ratio.

At fields of 50 milligauss and below where the second order splittings become negligible the spectrum simplifies to two components, one strong and one weak, separated by about 2.8 hertz per milligauss. Linewidths as narrow as three hertz (about 4 microgauss) with reduced signal-to-noise ratio have been achieved at such fields by using amplitude modulation of the R.F. field at about 10 hertz and very low light intensity and R.F. level. Sidebands corresponding to the modulation frequency are observed, but a rough measure of the width of the central peak can be obtained. Free precession measurements giving spin-spin relaxation times of roughly 0.15 sec at low fields for some samples indicate that somewhat narrower linewidths should be obtainable, but they would probably not be useful for magnetic field measurements because of lower signal-to-noise ratios and necessarily longer measuring times [5].

### B. *Self— oscillating Alkali Vapor Magnetometer.*

Dehmelt [6] and Bell and Bloom [3] pointed out in 1957 that a self-oscillating alkali vapor magnetometer could be constructed using the same optical pumping methods as in the D.C. version. The same type of light source, interference filter, circular polarizer, and sample are used, and the discussion will again be limited to rubidium—87 for simplicity. The light beam is at an angle between 0 and 90 degrees to the magnetic field direction and coils which can give an R.F. field along the direction of the light beam are provided.

When no R.F. is present a magnetization will build up in the sample along the direction of the field. This is because the optical absorption coefficient will be lowest, when averaged over the rapid precession about the magnetic field axis, for atoms having small angle between their magnetic moments and the field direction. If an R.F. field is present and if the second order splittings are small, the motion of the magnetization can be treated conveniently in a coordinate system rotating at the frequency of the applied field [7]. In this coordinate system the magnetization will precess about the sum of the R.F. field and the effective axial field due to the difference between R.F. and resonance frequencies. The precession in the rotating coordinate system and the continued optical pumping will lead to a steady state in which the magnetization of the sample precesses with some definite phase with respect to the R.F. field. The optical absorption coefficient of the sample will increase and decrease as the component of magnetization along the direction of the light beam changes. The output from the photodetector will thus be a signal at the R.F. frequency whose amplitude and phase are determined by the frequency and strength of the R.F. field and by the optical pumping process. The signal will be strongest at the resonance frequency and will then lag the R.F. field by 90 degrees.

If the photodetector output is amplified sufficiently, given a 90 degree phase shift, and fed back to the R.F. coils, the system will oscillate by itself at the resonance frequency. A measurement of the self-oscillation frequency then gives the value of the magnetic field.

The self-oscillating rubidium magnetometer has the advantage of requiring no modulation and of having a short response time. Several devices of this type have been constructed by Varian Associates (Palo Alto, California) for research use as station magnetometers. Noise levels of 0.1 microgauss have been reported for these instruments and measurements of correlation distances for micropulsations in the earth's field have been made with them [8].

A number of self-oscillating rubidium vapor magnetometers are also being developed by Varian Association for use by the U.S. National Aeronautics and Space Administration in various spaces probes [9]. In this application the requirements are severe. In addition to shock and vibration problems during launching there are other added complications. The field will in some cases vary by a large factor during measurements, and the orientation with respect to the field will normally change.

The most evident effect of orientation on the self-oscillator is the effect on signal strength. The signal will be strongest if the angle between the light beam and the magnetic field is roughly 45 degrees. If the angle is near 0 or 90 degrees the gain will be low and oscillation will not take place. The size of the dead zones can be reduced by improving the signal-to-noise ratio. A second effect of orientation is that the device as described above will not oscillate if the angle between the light beam and the magnetic field is more than 90 degrees unless the phase of the R.F. is switched by 180 degrees or the type of circular polarization of the light is changed. This difficulty has been overcome in some instruments by arranging for automatic shifting of the R.F. phase if no signal is present.

A third effect due to orientation occurs because of the second order splitting of the resonance lines. In the above discussions it was assumed that these splittings were small. When this is not the case the situation is considerably more complicated. If an R.F. field at the average frequency of the four componants of the main resonance is present the phase of the signal will in general be behind the R.F. field by some angle other than 90 degrees. The lag angle will only approach 90 degrees for extremely strong R.F. fields. However, if the magnetization precesses in the rotating coordinate system by much more than one radian on the average before absorbing a photon or undergoing relaxation due to some other cause, then the signal will be relatively weak. For a self-oscillating magnetometer with a built-in 90 degree phase shift the frequency will be that for which the gain is highest, subject to the condition that the phase lag be 90 degrees. Oscillation will thus take place at some frequency other than the average resonance frequency. Since the effective R.F. field strength and the details of the optical pumping process depend on the direction of the axis of the instrument with respect to the magnetic field, the oscillation frequency will depend on orientation. This effect will normally be important for fields of 0.1 gauss or more, but will not be significant for lower magnetic fields.

A modification of the self-oscillating rubidium vapor magnetometer which to a large extent avoids the last orientation effect mentioned above has been developed recently by Varian Associates. It involves the use of two gas cells in the oscillating loop. For this device the effect of orientation on frequency should cancel to the extent that the optical pumping conditions, R.F. field strengths, and output signals for the two cells are the same. This modification also has the advantages that a 90 degree phase shift is not needed and that oscillation will take place for angles greater than 90 degrees between the light direction and the magnetic field without the use of any switching arrangements.

It is of interest to compare the self-oscillating rubidium magnetometer with the D.C. device. For fixed application in the earth's field where high accuracy is needed and the field does not change rapidly, such as for calibrating other magnetometers, the D.C. device seems definitely preferable. This is because the second order splittings can be resolved and one component used for the measurement. For high accuracy measurements in the earth's field, potassium-39 is probably more desirable than rubidium-87. The second order splittings are much larger (3) and overlaps of components is then not a problem. Interference filters to separate the two principal optical resonance lines can be obtained despite to splitting of only 35 A, and the required sample operating temperature of about 65 C does not seem to be a serious limitation. For application where orientation is not maintained and fast response is desired the modified self-oscillator seems definitely more desirable. This is particularly true for space applications. For calibration purposes in low magnetic fields, where the second order splittings are negligible and the orientation does not change, both devices can be used. However, if the linewidth is comparable with the field strength, the observed resonance frequency will not be proportional to the magnetic field. The correction needed will depend on the light intensity, R.F. field strength and relaxation time. For very low fields free precession devices [10] may also be desirable. They have the advantage that the R.F. field is not present during the measurement. However, the optical pumping process will introduce asymetry of the signal, and this departure from an exponentially damped sine wave can cause difficulty if the period is comparable with the decay time. The self-oscillators, have the advantage of continuous operation, and they have been operated by Varian Associates and the National Aeronautics and Space Administration at fields as low as 30 microgauss with low light intensity and R.F. field strength. The lowest field at which oscillation can be achieved seems to be limited mainly by the signal-to-noise ratio rather than by the relaxation time for the sample.

### C. *Helium Magnetometer.*

A type of magnetometer using optical pumping in metastable helium was suggested in 1958 by Franken and Colegrove [11]. In the original version of this device light from a helium lamp is passed through a sample containing helium and the transmitted light is monitored by a photodetector. A weak discharge is maintained in the sample to provide helium atoms in the 2 $^3S_1$ metastable state, and an R.F. field at approximately the Zeeman frequency for the metastable state is applied at right angles to the magnetic field.

The metastable state can be considered as the ground state for the optical pumping process. A typical lifetime for this state is 0.2 millisec while the discharge is present. Atoms are exited from the 2 $^3S_1$ state by a group of three helium optical lines at about 10, 830 A ($D_0$, $D_1$, $D_2$) to the 2 $^3P_{0,1,2}$ levels, and fall back by spontaneous emission to the metastable state. The $D_1$ and $D_2$ lines are normally not resolved and thus have equal intensities, but the $D_0$ line is well resolved and its intensity is usually considerably lower because of its smaller statistical weight. For different intensities of the D lines the absorption coefficients for the metastable atoms will in general depend on whether they are oriented perpendicular to or along the magnetic field direction. Atoms will then accumulate in the states with low absorption coefficients. If the R.F. frequency is correct to cause Zeeman transitions in the metastable state the atomic orientations and thus the optical absorption coefficient will change. The signal will consist of a decrease in the amount of light reaching the photodetector when the Zeeman frequency of 2.8 megahertz per gauss is applied. For the special angle of 55 degrees between the light beam and the field direction the optical absorption coefficient will not depend on the atomic orientation, and thus no signal will be seen. Modulation of the magnetic field or frequency and phase sensitive detection can be used to lock the applied frequency to the center of the resonance line, and the field is then directly proportional to the output frequency.

There are a number of differences between the helium magnetometer described above and rubidium magnetometers. The frequency is a factor four higher than for rubidium—87 and there is no splitting of the line, since the nucleus of the normal helium isotope has no angular momentum or magnetic moment. The linewidth is determined by the lifetime of the metastable state and is usually of the order of a milligauss, although observed lifetimes of up to 20 millisec for metastable helium atoms in pulsed discharges indicate that considerably narrower lines are possible if perturbations due to the discharge can be avoided. Since only helium is used in the lamp and sample temperature control problems are minimized. The response time can be quite short because of the higher frequency and comparatively broad resonance line. On the other hand the width of the resonance requires particular care in design of the electronics if high precision measurements are to be made over extended period of time.

Several models of the helium magnetometer have been developed by Texas Instruments, Inc. (Dallas, Texas) in order to investigate the sensitivity which can be achieved [12]. In recent ones circularly polarized helium light has been used in place of unpolarized light, with a resulting improvement by about a factor 40 in the signal-to-noise ratio. The best linewidth which has been achieved is 730 microgauss with a bandpass of 0.2 hertz to 10 KHz and a signal-to-noise ratio of the order of several hundred. The usual linewidth is 1500 to 2500 microgauss with a signal-to-noise ratio of up to 500, excluding 60 hertz pick-up. In order to lock an oscillator to the resonance, a modulation frequency of 45 to 130 hertz and a phase sensitive detector are used. A sensitivity of about 0.1 microgauss have been achieved with a bandwidth of 0.04 to 0.7 hertz.

A model intended to be independant of orientation has been developed recently. The signal-to-noise ratio and hence sensitivity varies by less than a factor two with orientation. This model is intended for use in flight tests. (Recently, some orientation dependance of the signal frequency has been found by Texas Instruments with a helium magnetometer using circularly polarized light. Stark shifts due to electric fields in the discharge are believed to cause this effect. The use of two samples with opposite Stark shifts would reduce the orientation dependance to the extent that the signal strength and shift were the same for the two samples.)

In comparing the helium magnetometer with the self-oscillating rubidium magnetometer it is necessary to keep in mind that the present limitations are practical rather than theoretical ones. The noise level, long terms stability, orientation independance, accuracy, power, weight, and size all depend on the degree to which the device have been engineered. The difficulties of developing production models of these two instruments to the point of having a low frequency sensitivity and an orientation independance of 0.1 microgauss in the earth's field appear at present to be comparable. For absolute measurements of the earth's field at quiet times it seems that the D.C. alkali vapor magnetometer will continue to be more desirable unless the linewidth for the helium magnetometer can be reduced considerably. The difference in linewidths also appears to favor alkali vapor magnetometers for use in very low fields.

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