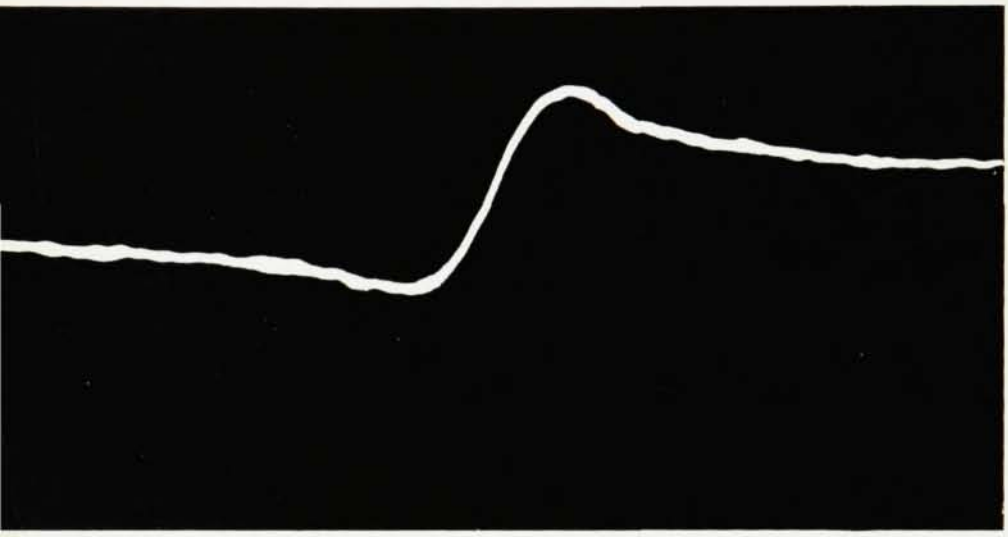
NUCLEAR INDU



Recent developments are discussed in this article which was adapted from an invited paper presented before the American Physical Society at its meeting in Washington, D. C. this spring.

by ***Felix Bloch***

It is now somewhat over four years since the phenomenon was discovered which is alternately known as "nuclear magnetic resonance absorption" or "nuclear induction". In the meantime it has become so widely known among physicists that it seems hardly necessary any more to explain it. Nevertheless, for the benefit of those who have not followed closely the developments we shall start with a brief recapitulation of the basic principles.

As the shortest general description of the phenomenon one can say that it consists of the electromagnetic effects accompanying the reorientation of nuclear moments. To achieve a substantial reorientation, one makes use of the principle of "magnetic resonance", first used successfully at Columbia University in the research on molecular beams, where an alternating magnetic field is applied at right angles to a constant field with its frequency equal to the Larmor frequency of precession of the nuclei in the constant field. The frequencies thus required are at normal conditions in the range of short radio waves. The essential difference lies in the detection of nuclear reorientation which is not achieved here by observing a different path of the molecules as

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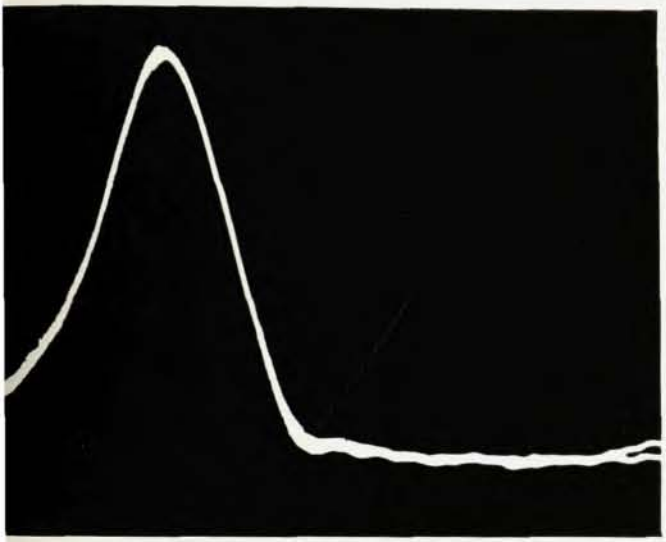

These nuclear induction signals are from protons in water in which is dissolved a slight amount of manganese sulphate to accelerate the establishment of thermal equilibrium. The illustration on the left represents a dispersion signal, that on the right an absorption signal. One obtains one or the other (or some intermediate signal) by adjusting the phase component of the observed signal with respect to the driving radio-frequency field.

in the work with molecular beams, but by the effects upon suitably designed radio-frequency circuits. These effects can be interpreted and observed in many different ways. One can speak about absorption or dispersion, one can observe the regeneration or the frequency change of an oscillating circuit, one can utilize the reaction upon the system which provides the alternating field or use a separate receiver system for observation. In any case, the effects can be traced back to the induced electromotive force which has been known, since the days of Faraday, to accompany a change of the magnetic induction, and which is here due to the change in orientation of nuclear magnetic moments. It is for this reason that the term "nuclear induction" seems most suitable and descriptive of the phenomenon as a whole, and it shall be used in this general sense.

With this understanding it can be stated that research on nuclear induction has progressed in various directions and in many laboratories, in this country notably at Harvard, MIT, Rutgers University, Brookhaven, the Bureau of Standards, Ohio and Illinois State Universities, Chicago, St. Louis, and Stanford. Progress has been in the direction of higher sensitivity, greater accuracy, and a wider range of applications. This account will be restricted to a few special topics, not because others are considered of less importance but merely because of limited space and the fact that the author has recently been most concerned with these selected topics.

We shall start with the problem of measuring with high precision the magnetic moments of different nuclei. It is based upon the fact that the (circular) Larmor frequency of precession, and hence the resonant frequency, of the alternating field is given by the product of the "gyromagnetic ratio" of the nucleus under investigation and the magnitude of the applied constant magnetic field. The gyromagnetic ratio is equal to the ratio of the magnetic moment and the angular momentum of the nucleus; measured in units of Planck's constant, divided by 2π, the latter is called the spin of the nucleus and is always a multiple of $\frac{1}{2}$.

There are several different methods of ascertaining the spin; once it is known, the problem of measuring the magnetic moment is equivalent to that of measuring the gyromagnetic ratio. The most accurate determinations of nuclear moments are relative: nuclei whose moments are to be determined are placed in the same sample and thus in the same field as certain "standard" nuclei of comparison; their gyromagnetic ratio is then equal to that of the standard, multiplied by the ratio of the corresponding resonance frequencies. The value of the constant field does not enter at all into such a comparison and

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the relative accuracy is given by that with which either of the two frequencies can be measured, i.e., by the number of cycles which take place during a coherent observation.

In molecular beams this number is limited by the time which a molecule spends in traversing the apparatus and is, under favorable conditions, of the order of ten thousand. In observations of nuclear induction, the nuclei do not leave the recording apparatus; the coherence of observation is, however, interrupted by irregular interaction processes of the moments with the atoms and molecules in their neighborhood. The average time between such processes, or relaxation time, can sometimes be found to comprise the order of a hundred thousand cycles and thus offers the possibility of a corresponding accuracy. Relative accuracies of this order are of particular interest for the isotopes of hydrogen and have actually been obtained.

By a series of relative measurements the nuclear magnetic moments can all be expressed in terms of an ultimate standard, and the proton has been found to be most suitable for this purpose. The problem arises then of measuring the magnetic moment of this standard, which is of considerable interest itself as belonging to one of the two nuclear constituents. During the last twenty years the proton moment has been repeatedly measured by different methods and with increasing accuracy. Depending upon the method, the result is found in units of different fundamental constants, so that new relations can be established between these constants. Just during the last year several new methods have been applied, all leading to results with an accuracy of approximately one part in ten thousand.

Of these methods we shall particularly mention one which gives the proton moment in terms of the nuclear magneton, the natural unit of nuclear physics and defined as the Bohr magneton multiplied by the mass ratio of electron to proton. It was first applied over ten years ago in a rather crude calibration of the magnetic moment of the neutron and is based upon the cyclotron motion of protons. To be more specific, consider the frequency of a proton as it moves around a circle in a homogeneous magnetic field and, in the same field, the Larmor frequency of precession of a nuclear moment, belonging to a nucleus with spin $\frac{1}{2}$, such as a neutron or a proton. It can be shown that the two frequencies are to each other in the same proportion as the nuclear magneton to the magnetic moment of the nucleus. The value of the latter in nuclear magnetons is thus again obtained by the measurement of a frequency ratio with similar limitations on accuracy to those mentioned above. For protons, the Larmor frequency is obtained by observing through nuclear induction the resonance frequency in a sample of water; the frequency of orbital motion can be obtained by observing the accelerating or decelerating cyclotron action of an electric field in a small region, and either of the two actions has been utilized with similar accuracy to obtain the magnetic moment of the proton.

Another recent development is the application of nuclear induction to a great variety of nuclei, with the result that the more accurate knowledge of the values of most magnetic moments is now due to this method. The nuclei are studied in solid, liquid, or gaseous samples or in compounds dissolved in a liquid. The choice of the sample is determined by considerations of density, chemical nature, and relaxation time. It is characteristic of the considerable gain in sensitivity over the earlier work that observations can be carried out on isotopes of low abundance and with relatively small moments and that gases without excessive pressure can be used.

It must be mentioned here that proper use of the method allows not only determining the gyromagnetic ratio of a nucleus but also, separately, the spin and the sign of the magnetic moment. The sign of a magnetic moment refers to its orientation relative to the angular momentum and the convention has been accepted of speaking about positive or negative moments in cases where this relative orientation is the same as that which exists for a rotating mass point with positive or negative electric charge, respectively; in this sense the proton has a positive, the neutron a negative moment. If the alternating field originates from currents flowing in a coil and the induced electromotive force is observed in another coil with the axes of the two coils perpendicular to each other and to the constant field, one can show that the sign of the magnetic moment is manifested by the phase relation of the voltage in the two coils. By superposition of the two voltages and subsequent rectification it is directly related to the sign of the observed rectified voltage. There is a third piece of information to be obtained from nuclear induction, i.e., the relative magnitude of the observed induced voltages. With a known density of nuclei, this makes

it possible from the resonance frequency, the sign, and the magnitude of the observed signal voltages to infer not only the gyromagnetic ratio and the sign, but also separately the spin, and hence the magnitude of the nuclear magnetic moment.

While only the moments of the few very lightest nuclei can be directly interpreted in terms of nuclear forces and are therefore probably of the greatest fundamental significance, those of the heavier nuclei are nevertheless also of considerable interest. Their values have given considerable support to the hypothesis of nuclear shell structures; more supporting evidence has recently been obtained from nuclear induction. In this context it is sufficient, at present, to obtain data with a relative accuracy of a few per cent; the considerably higher accuracy which nuclear induction can furnish is however significant in isotopes of the same element. This is particularly true in view of the fact that corresponding data concerning the hyperfine structure can frequently be obtained with comparable accuracy from the magnetic resonance observed in atomic beams. It was originally thought that the ratio of hyperfine structure separations could be uniquely interpreted in terms of the ratio of the magnetic moments pertaining to isotopes. When both are measured independently and with high accuracy, there appear, however, small discrepancies, and they often allow most interesting conclusions concerning the effect of the specific nuclear structure upon the interaction with atomic electrons.

In measuring the magnetic moment of nuclei with spin $\frac{1}{2}$ one has a considerable freedom in the choice of samples. Since liquids lead usually to sharper lines than solids, it is often advantageous to use solutions. To insure sufficient concentration the compound is here chosen primarily with regard to high solubility. It is sometimes more difficult to find the proper compound for the element under investigation if one deals with nuclei of higher spin. In this case there exists the possibility that the nucleus, besides its magnetic dipole moment, possesses also an electric quadrupole moment, and the inhomogeneous electric fields originating from the molecular surrounding may therefore cause an excessive broadening of the resonance line. To prevent this feature and the ensuing difficulty in observing nuclear induction, one must choose a compound where the symmetry of the molecule results in an effective cancelation of the broadening electric field gradients at the location of the nucleus under investigation.

It has recently been found that the choice of the compound can have an effect not only upon the width of the resonance but also upon the frequency at which it occurs. Identical nuclei, observed in the same external field, can lead to different frequencies if they are contained in different molecules, and the corresponding lines can be separated by an interval, well exceeding their width. Thus an aqueous solution of ammonium nitrate leads to two sharp nuclear induction signals from nitrogen, separated in frequency by about one part in two thousand, of which one can be ascribed to the positive ion of NH_4, the other to the negative ion of NO_3. This phenomenon is not connected with the existence of nuclear electric quadrupoles, since it can occur for nuclei of spin $\frac{1}{2}$ as well as for those of higher spin; it must be ascribed to the fact that the magnetic field which causes the precession of the moment is not exactly equal to the external field but that its value is modified by electrons in the neighborhood of the nucleus. It has been understood for a considerable time that the mechanism which leads to the diamagnetic susceptibility of a substance would, at the same time, result in a slight shielding of the external field by the atomic electrons at the location of the nucleus. Considering, however, that only the outermost electrons are affected by the chemical binding, the observed effects are too large to be explained by a difference of diamagnetic shielding in different compounds. In certain compounds of cobalt, the effect can exceed one percent, and while this is quite an anomalous case, it indicates that more detailed considerations of molecular structure will be required to explain the observed chemical effects. They determine at present the limiting accuracy in our knowledge of many nuclear moments, since resonance frequencies are often more accurately known than the influence of the external electrons upon the effective value of the magnetic field. Experiments have shown, however, that this limitation does not apply to determinations of the ratio of moments when carried out for isotopes of the same element.

The influence of the chemical binding upon resonance frequencies requires further systematic studies. It may be hoped that they will remove the present uncertainties and contribute to the understanding of this small but interesting effect which has been revealed through the great precision with which measurements of nuclear induction can be carried out.