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NUCLEAR MAGNETIC RESONANCE AND THE STRUCTURE OF MATTER

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A diamagnetic substance placed in a static magnetic field and also subjected to an alternating magnetic field of certain frequency will absorb energy from the alternating field. This phenomenon is known as nuclear magnetic resonance because it is due to the nuclear magnetic moments present in the molecules of diamagnetic substances. Nuclear magnetic resonance was first observed

by Bloch[1] and independently by Purcell. Bloch's experiments were based on the fact that a reorientation of the nuclear magnetic moments (related to the angular momentum or spin) gives rise to an induced electromotive force. These experiments are analogous to those of Zavoiski where resonance absorption was observed as a result of a reorientation of the electronic magnetic moments.

Soon after Bloch's experiments it became clear that nuclear magnetic resonance could be used for investigating the structure of matter (e.g. determination of the nuclear magnetic moments, study of molecular and crystal structure, chemical analysis, etc.) Since 1946 this method has developed rapidly; today many hundreds of nuclear magnetic resonance experiments are made and their number grows continuously. It should be pointed out that the discovery and the rapid development of the method were made possible by the progress made in radio-frequency techniques. In this article we shall not deal with problems of technique but we shall try rather to explain the physical principles of nuclear magnetic resonance and indicate certain fundamental applications in the study of the structure of matter.

A nucleus with angular momentum (spin) I possesses also a magnetic moment μ which is parallel or antiparallel[2] to I. The two quantities are related in such a way that $\mu = \gamma I$, where γ is the gyromagnetic ratio of the nucleus (it would be more correct to call γ the magnetogyric ratio since it is the ratio of the magnetic moment and angular momentum of the nucleus). The constant γ, which depends on the nuclear structure, is an important characteristic of the nucleus together with its mass, charge, and angular momentum (spin). For a nucleus which is not subjected to any external forces, the vector I remains unchanged because of the conservation of angular momentum. The situation is different, however, when the nucleus is placed in a static magnetic field H_0, directed along the z-axis, for example. In this case the angular momentum of the nucleus changes; the equation of motion shows that the vector I, though retaining its absolute value, changes direction in space in such a way that it precesses about H_0 with an angular frequency $\omega_0 = \gamma H_0$. This is known as the Larmor precession. The behaviour of vector I can be compared to the precession of a spinning top in the gravitational field.

It is more convenient to explain many physical processes associated with nuclear magnetic resonance in terms of a frame of reference rotating around H_0. We can thus observe the behaviour of the nuclear magnetic moment (which is parallel or antiparallel to I) from the rotating frame of reference. When the angular frequency of its rotation is equal to ω_0, both the magnetic moment and the angular momentum remain stationary as if the external field were absent. Consequently we can say that in the system of coordinates rotating with frequency ω_0 the external magnetic field is zero. However, when the frequency of rotation ω is not equal to ω_0, I and μ perform the Larmor precession with the angular frequency $\omega_e = \omega_0 - \omega = \gamma H'_e$. That is to say, in the rotating system of coordinates there is an effective field $H'_e = H_0 - \omega/\gamma$, which is parallel or antiparallel to H_0.

Let us suppose now that in addition to H_0 we also have an alternating field H_1 which rotates with frequency ω, i.e. the same frequency as that with which the system of coordinates is rotating. In this system H_1 is therefore stationary. Let H_1 be directed along the x-axis of the rotating system. The resultant magnetic field H_e is then obtained by using the vector addition rule as shown in Fig.1.

In the rotating system μ precesses around H_e with Larmor frequency equal to γH_e. Obviously when H_1 rotates with frequency ω_0, then $H'_e = 0$, and $H_e = H_1$. In this case μ precesses around the x-axis (i.e. the H_1 direction) with angular frequency γH_1; for example, if initially μ was along the z-axis then after a time $t = \pi/\gamma H_1$, the vector μ changes its direction by 180°. However if ω is very different from ω_0, that is, $|\omega_0 - \omega| \gg \omega_0 H_1/H_0$, and H_1 is considerably smaller than H_0, then H_e is nearly parallel to H_0 and in the stationary system of coordinates (in which the z-axis coincides with the z-axis of the rotating system) the motion of μ will be very nearly the Larmor precession of μ about the static field H_0, in other words, the motion of the magnetic moment will not be appreciably affected by the presence of H_1.

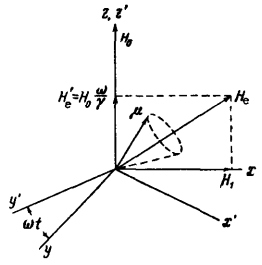


Fig. 1. The magnetic fields in the rotating coordinate system. Coordinates $x\,y\,z$, equal to the frequency of rotation of H_1. H_e is the effective field in the rotating coordinates with $H_1 = 0$. When H_1 is applied, the magnetic-moment vector μ precesses around H_e, (which lies in the xz-plane) with angular frequency $\omega_e = \gamma H_e$.

The mechanism described above forms the basis of nuclear magnetic resonance. Fig.2 represents schematically a typical nuclear-magnetic-resonance experiment.

Sample S containing a large number of magnetic nuclei is placed in a static magnetic field H_0 (H_0 is perpendicular to the plane of the drawing). Since the energy of the magnetic moments in the external magnetic field H_0 depends on their relative orientation, there will be a larger number of

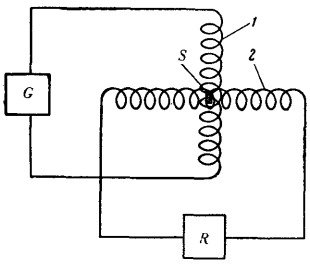


Fig. 2. The principle of a nuclear-magnetic-resonance experiment. G – radio frequency generator ($\omega \sim 10$ Mc/s); S – sample; R – receiver used to pick up the induced signals; (1) and (2) are induction coils. The receiver for detection of the absorption signal is not shown in the diagram.

moments aligned along H_0 than in the opposite, energetically unfavourable, direction. This alignment is brought about by the interaction of the magnetic moments and the thermal agitation of the medium (translational and vibrational molecular motion, vibration of the crystal lattice, etc.). In this way the sample becomes polarised and acquires a finite net magnetic moment M_0 directed along the z-axis.

It should be pointed out, however, that complete polarisation is not attained immediately after the application of H_0. The time of polarisation depends on the interaction of the nuclear magnetic moments with the lattice and can be approximately characterised by a quantity T_1, called the longitudinal relaxation time, which determines the time in which the net magnetic moment of the sample reaches its equilibrium value M_0. For typical samples T_1 ranges from a fraction of a second to an hour, e.g. for protons in pure water $T_1 \cong 2$ sec but in LiF T_1 approaches 50 min for Li.

Suppose the sample is subjected to the static field H_0 for a time $t \gg T_1$ so that it becomes completely polarised. Subsequently we switch on the generator G, working at a frequency $\omega_0 = \gamma H_0$ and generating a rotating field H_1 in coil *1* (the term "rotating field" is used in the sense that the field-intensity vector of the alternating field H_1 rotates with respect to the static field H_0)*.

If the generator is applied for a time $t_1 = \pi/2\gamma H_1$, then all the nuclear magnetic moments, initially along the z-axis, will be aligned along the y-axis in the rotating system of coordinates. Consequently the resultant magnetic moment of the sample having the absolute value equal to M_0 will be directed along the y-axis after time t_1, assuming that during this interval there is no appreciable relaxation, i.e. we assume that $t_1 \ll T_1$. For the gyromagnetic ratio of the order of 10^4 oersted^{-1} sec^{-1} and $H_1 \sim 10$ oersted, t_1 must be about 10^{-5} sec, which means that the condition $t_1 \ll T_1$ can be easily satisfied. Moreover, the condition that $H_1 \ll H_0$ is also readily fulfilled since in most nuclear-magnetic-resonance experiments H_1 is about 10 oersted and H_0 is of the order of 10^3 to 10^4 oersted.

When the alternating field is switched off all the nuclear magnetic moments precess about H_0 with angular frequency $\omega_0 = \gamma H_0$, and therefore so does the resultant magnetic moment M (directed along the y-axis of the rotating system of coordinates). The rotating moment M generates an alternating field in coil *2* and induces a voltage across the coil. This voltage is amplified and fed into a receiver R. The signal observed in this way is known as the free-induction signal.

The signal decays in time T_1, because during this interval the sample is repolarised and its magnetic moment is again directed along the z-axis. In fact, the free-induction signal decays in a time shorter than T_1 because the relaxation of the transverse component of M (perpendicular to H_0) is faster than (or equal to) the relaxation of the longitudinal component (parallel to H_0). The physical reasons for this are readily understood. Suppose that H_0 is somewhat inhomogeneous over the sample. We can express the degree of inhomogeneity in terms of $\Delta H = [\overline{(H_0 - \overline{H}_0)^2}]^{\frac{1}{2}}$, where the bar indicates the average taken over the sample. ΔH_0 therefore is the measure of H_0 deviation from the mean value $\overline{H}_0$ (in cases where ΔH is small and the effect of field inhomogeneity in so far as the nuclear moments are subjected to slightly different fields H_0 they will be turned through slightly different angles on application of the alternating field in the experiment described above. These differences will be small and of the order of $\Delta H / H_0$, so that soon after the alternating field is applied, the net magnetic moment of the sample, will have the absolute value approximately equal to M_0 and will point along the y-axis as before. However, when this field is switched off, the nuclear moments situated in slightly different H_0's will precess with somewhat different frequencies. Consequently, even in the absence of the longitudinal relaxation, the transverse component of M decays in a time of the order of $1/\gamma \Delta H$, which is equal to the difference between the extreme Larmor precession periods of the nuclear moments. But even if H_0 is perfectly homogenous, there remains an internal magnetic field due to the nuclear magnetic moments in the sample. This field, which is substantially inhomogeneous, causes relaxation of the transverse component of M without affecting its longitudinal component. On the other hand, the spin–lattice interaction controls the decay of both the longitudinal and the transverse components of M. In this way the decay of the latter is faster, that is to say the transverse relaxation time T_2 is less than T_1.* For example in LiF T_2 is of the order of a few milliseconds, whereas T_1 is many minutes. But in a large number of substances, including gases and the majority of liquids, at room temperature, $T_1 = T_2$. In these substances the local magnetic fields fluctuate very rapidly compared to the Larmor frequency ω_0 (for $H_0 \cong 10^3$ oersted, $\omega_0 \cong 10$ Mc/s), and therefore in one Larmor period a nuclear magnetic moment goes through many different local fields so that on average its precession frequency is not affected. It should be noted that in certain liquids $T_2 \neq T_1$ which indicates a restricted molecular mobility (large viscosity, presence of quasicrystalline structure, formation of molecular complexes, etc.).

The mechanism described above explains these physical processes from the classical point of view only. A more precise description requires quantum mechanics[4,5] which reveals a number of additional relaxation processes without any classical analogues. In spite of the fact that nuclear magnetic relaxation has been extensively studied, there is as yet no complete theoretical treatment of this problem which would allow accurate quantitative analysis of experimental results.

The free-induction experiment discussed above is performed in a time short compared to T_1 or T_2. The spin-echo experiment described below also belongs to the same class[6-8].

* In actual fact an oscillatory field is produced in coil *1*, equal to $2H_1 \cos \omega_0 t$ but this can be represented by two rotating components of amplitude H_1 and angular frequencies ω_0 and $-\omega_0$. One of the components (with frequency $-\omega_0$) does not affect the nuclear-magnetic-moment motion because it is too far away from the resonance condition, i e. $|-\omega_0 - \omega_0| \gg \omega_0 H_1 / H_0$ (see text).

* Since T_1 and T_2 are unequal, the absolute value of the net magnetic moment of the sample may change during the relaxation process. It is therefore necessary to use at least two parameters, T_1 and T_2, to describe the process.

Suppose the sample is placed in a non-uniform magnetic field H_0 such that the decay of the transverse component of M caused by the field inhomogeneity is faster than the decay due to the internal relaxation processes. After the vector M is turned through 90° by the alternating field the individual nuclear magnetic moments precess with slightly different frequencies because of H_0 inhomogeneity. At a time τ ($\tau \ll T_1$ or T_2) when the free-induction signal has decayed completely, we again apply the alternating field which rotates each nuclear magnetic moment around the x-axis of the rotating system of coordinates. By adjusting the time during which this field is applied it is possible to reverse the phases of the precessing nuclear moments. Since the frequencies of precession remain unchanged by this procedure, all the nuclear magnetic moments will again be aligned at a time τ after the second pulse in the same way as they were after the first pulse. This will lead to a free-induction signal induced in coil *2*. The shape of the signal depends on the H_0 distribution over the sample. This signal is known as the spin echo. We can use the following simple analogy to illustrate this phenomenon.

Let us suppose that a group of runners has started simultaneously from the starting line (the first pulse). Though all the runners were initially in one line, after some time has elapsed, they will spread along the track because of the differences in their individual speeds (the decay of the free-induction signal). At a time τ all the runners turn back and continue to run at their previous speeds (the second pulse). It is quite clear that at a time τ later they will reach the starting line simultaneously (the spin-echo signal). Using this model, we can also show how the field inhomogeneity governing the Larmor frequency distribution determines the shape of the signal. If our runners have very different speeds then they will be grouped together only just before they reach the starting line on their return (narrow signal); on the other hand if they have very similar speeds they will bunch together even a long way from the starting line (broad signal).

Another class of nuclear-magnetic-resonance experiments makes use of nuclear magnetic absorption. These experiments are performed in a time long compared to T_1 or T_2. The alternating field is applied continuously and not in pulses so that the nuclear magnetic moments continuously precess around the H_1 direction (in the rotating system of coordinates). The relaxation processes tend to repolarise the sample and restore the equilibrium (disturbed by the alternating field) between the spin system and the thermal agitation of the medium. There is then a net transfer of energy from the alternating field to the thermal motion of the medium via the nuclear magnetic moments; in other words, the sample is heated. Naturally the heating effect is very small because at normal temperatures the energy of thermal motion is considerably higher than the interaction between the nuclear spins and H_0. Nevertheless, it is possible with the aid of modern amplifiers to detect this absorption of energy occurring in coil *1*, when the resonance condition ($\omega = \omega_0$) is satisfied. We can obtain a spectrum of the nuclear absorption (or induction if we observe the signal in coil *2*) by varying the frequency of the generator or by changing the magnitude of H_0. We can in this way measure the differences between the nuclear-magnetic-moment energy levels. In principle, this phenomenon is identical with optical absorption (or emission)

We shall now discuss some of the basic applications of nuclear magnetic resonance.

In the first place, since $\omega_0 = \gamma H_0$, we can determine the nuclear gyromagnetic ratio by measuring ω_0 and H_0. The magnetic field cannot as yet be measured very accurately, but the resonant frequency can be determined with great precision. This means that the accuracy achieved in absolute measurements of the gyromagnetic ratio is limited by the degree of precision with which the magnetic field is determined. It should be possible to make relative measurements of γ as accurately as the determination of frequency. Unfortunately any non-uniformity of H_0 broadens the magnetic-resonance absorption line (nuclei subjected to slightly different H_0 display absorption at slightly different frequencies). This limits the resolving power of the apparatus. The accuracy is further limited by any instability of H_0. The manufacture of high-stability magnets producing very homogeneous fields presents a complex technical problem. Nevertheless, the nuclear-magnetic-resonance spectrometers now available have resolving powers of up to 10^8, i.e. it is possible to resolve two resonance lines separated by a fraction of a cycle while their resonant frequencies are of the order of 10 Mc/s.

The resonant frequency of a given nucleus depends on the molecule which contains the nucleus and on its position in the molecule. This displacement of the resonant frequency depending on the molecular structure is known as the chemical shift. The shift is due to the fact that each nucleus is surrounded by an electron cloud which under the influence of the external field H_0 produces a diamagnetic moment giving rise in turn to a magnetic field $-H'$ at the site of the nucleus. H' is proportional to H_0, i.e. $H' = -\sigma H_0$. One could say that the nucleus is magnetically screened and that in fact it is subjected to a field $H_0' = (1 - \sigma)H_0$ instead of H_0. The magnetic screening constant σ, and consequently the effective static field H_0' and the resonant frequency, depend on the molecule and on the position of the nucleus in the molecule. The chemical-shift studies are therefore of particular interest from the point of view of physical chemistry and molecular physics[9]. We shall now give a few examples.

First of all, the chemical shift can be used as an analytical tool in a way analogous to optical-spectrum analysis, i.e. by making a systematic classification of the magnetic-resonance lines associated with specific molecules and atomic groups we can subsequently establish the presence of a certain atomic group in the sample from the presence of these lines in its spectrum, and from their intensity we can determine the concentration of the group. So far this method has not been much developed and its accuracy is inferior to other analytical procedures, but it has the great advantage that it affects neither the chemical composition of the sample nor its molecular motion, which cannot be said, for example, of the emission spectrum analysis.

Secondly, nuclear-magnetic-resonance spectroscopy can be used to determine various isomeric molecular structures. As an illustration of the method let us consider the nuclear-magnetic-resonance spectrum of ethyl alcohol, C_2H_6O (Fig.3). The spectrum consists of three lines corresponding to the three non-equivalent proton positions. Furthermore, since the areas under these lines (i.e. their integral intensities) are in the ratio 3 : 2 : 1, we conclude that the number of protons in the first, second, and third non-equivalent positions is in the same ratio. Finally, knowing that the total number of protons in the molecule is 6, we arrive at the following structure: CH_3-CH_2-OH. In this case, of course, the molecular structure could be easily obtained without the aid of nuclear magnetic resonance but in more complicated molecules the method is extremely valuable.

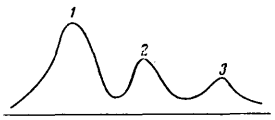


Fig. 3. Nuclear-magnetic-resonance spectrum in liquid ethyl alcohol showing the chemical shift. Lines *1*, *2*, and *3* correspond to the protons in CH_3, CH_2, and OH groups respectively.

Finally, the chemical shift contains information about the electronic-cloud structure. But before we can use the available data on chemical shift, we must have theoretical estimates of the screening constants. There are many papers on this subject, but because of the great mathematical difficulties involved any accurate calculation of the screening constants is apparently impossible without the aid of an electronic computer.

In addition to showing a chemical shift, nuclear-magnetic-resonance lines, are often split, owing to the intramolecular interaction between nuclear magnetic moments. As pointed out above, the magnetic interaction between neighbouring nuclei gives rise to the relaxation phenomena. This interaction broadens the resonance line, but it does not produce any splitting since its magnitude depends on the orientation of the molecule with respect to the external static field H_0. The line splitting is due to the fact that the nuclear magnetic moment polarises the electronic cloud of the molecule, which in turn creates an additional magnetic field at the neighbouring nucleus. This effect does not depend on the external field H_0. The magnitude of the splitting associated with this "indirect coupling" is, like the magnetic screening constant, dependent on the electronic-cloud configuration in the molecule; it therefore provides yet another method for studying molecular structure. Examples of such spectra and detailed lists of many papers on magnetic resonance may be found in the literature[10-12].

In crystals the transverse relaxation time T_2 is considerably shorter than in liquids. The presence of non-uniform local magnetic fields results in a very broad line (by comparison with liquids), whose shape reflects the local-field distribution. If the local-field inhomogeneity is determined solely by the adjacent magnetic nuclei, then it is possible to establish their configuration in the lattice. Several crystals have been examined in this way and proton positions determined with precision comparable to the neutron scattering method; protons are not easily located by X-ray.

Any rapid motion in the sample averages out local-field inhomogeneities and the resonance line becomes narrow. This phenomenon is found in crystals when certain atomic groups begin to rotate. We can thus investigate the nature of the internal motions of a crystal by observing its line width as a function of temperature.

Let us finally consider an interesting effect connected with chemical exchange in liquids[13]. If in a liquid there is a chemical equilibrium $AH \rightleftharpoons HB$, then the proton-exchange frequency between the A and B groups governs the shape of the proton-resonance line. When the exchange frequency is sufficiently low (in the limiting case there is no exchange of protons), the protons contained in the AH group have a resonant frequency ω_{pA} and those in the HB group resonate at ω_{pB} ($\omega_{pA} \neq \omega_{pB}$ because of the chemical shift). The situation is changed when the proton-exchange frequency is greater than $\omega_{pA} - \omega_{pB}$. We can easily see the effect by considering the motion of a proton magnetic moment from the point of view of an observer situated in a frame of reference rotating with frequency $\frac{1}{2}(\omega_{pA} + \omega_{pB})$. When the proton is in molecule AH, its magnetic moment, in the rotating system of coordinates, precesses with frequency $\frac{1}{2}(\omega_{pA} - \omega_{pB})$, but when it is contained in the HB group the proton precesses with the same frequency but in the opposite direction. Therefore, when the rate of exchange is much faster than the proton-precession frequency, in the rotating system of coordinates the proton remains stationary. Consequently, there will be only one resonance line in the spectrum corresponding to the frequency equal to $\frac{1}{2}(\omega_{pA} + \omega_{pB})$.

If the rate of exchange is equal to $(\omega_{pA} - \omega_{pB})$, then the line will have some intermediate form which, if known, will enable us to determine the proton-exchange frequency.

Soon after nuclear magnetic resonance was discovered, it was applied to the study of crystalline and amorphous polymers. Powles[14], for example, has shown that in amorphous polyisobutylene (repeating unit $-(CH_3)_2-CH_2-$) the distance between the hydrogen atoms belonging to the CH_3 groups in neighbouring repeating units can be less than twice the hydrogen van der Waals radius. Later, it became evident that the regularity of the side-chain configuration influences the line width and this fact makes it possible to study this important property of polymers.

Most of the nuclear-magnetic-resonance experiments in polymers are devoted to the study of their thermal motions (see the detailed review by Slichter[15]). The line width is reduced and T_1 and T_2 are altered by these motions, and therefore by measuring these quantities as a function of temperature we can obtain information about the nature of the motion and of transitions between solid and liquid phases, such as crystallisation and glass formation. The results obtained from such nuclear-magnetic-resonance measurements turn out to be in general agreement with dielectric and mechanical data. Nuclear magnetic resonance thus supplements other methods used in the investigation of molecular movements, but, unlike the dielectric method, it can be applied to substances devoid of polar groups. Also, the application of the magnetic field to the sample has no effect on the molecular motion; this cannot be said of either the mechanical or the dielectric method.

Study of the dependence of T_1 and T_2 for polymers on temperature and frequency[16,17] reveals very complex molecular motions in polymers. In particular, on raising the temperature of molten polymers, T_1 and T_2 do not approach each other, as they do in liquids of small molecular weight (see above).

The so-called crystalline polymers are not completely crystalline because they contain a certain amount of the amorphous phase. At temperatures above the glass transition temperature, and below the melting point, the amorphous part is in a fluid state and gives rise to a narrow resonance line, whereas the crystalline part has a broad line. The resulting compound line is a combination of a narrow line superimposed on a broad one. In a num-

ber of cases it is possible to separate the narrow and the broad lines and determine the degree of crystallinity from the areas under these lines. Unfortunately this method for determining the degree of crystallinity has a very limited application, because it is not always possible to separate the two lines.

Resonance lines composed of a narrow and a broad line are also observed in polymers containing low-molecular--weight components which move much more rapidly than the molecule of the polymer[18]. In the process of polymerisation by cross-linking the molecular movements change; this makes it feasible to study polymerisation kinetics by nuclear magnetic resonance. We have to remember, however, that the line width and the relaxation times refer to the entire polymer only if it has a comparatively low molecular weight. For polymers with long molecules, the line width is not determined by the motion of the molecule as a whole but by the motion of its segments with independent orientations.

In view of the high viscosity of polymer melts, their chemical shifts and nuclear-magnetic-resonance spectra can be obtained only in solutions. Some experiments of type, showing good resolution of lines in magnetic--resonance spectra of polymer solutions, have recently (1959) been reported in literature[19,20].

In conclusion let us consider briefly the recently developed electron and nuclear double-resonance method. This method is employed for studies of paramagnetic samples, i.e. samples containing an appreciable number of unpaired electrons (and consequently, an appreciable number of electronic magnetic moments, which are about 10^3 times larger than the nuclear moments). Obviously, the local magnetic fields are extremely large so that the nuclear--resonance line becomes too broad to be observed. On the other hand, the electron-paramagnetic-resonance lines[21] are so broad that it is also impossible to distinguish the components corresponding to the energy levels of individual nuclei. Therefore in order to obtain information about the energy levels of the nuclear spins, we can try to act simultaneously on the electronic and the nuclear moments by means of an alternating magnetic field. This is exactly what is done in a double-resonance experiment. That is to say, the principle of the double-resonance experiment is to apply an additional alternating field at a frequency corresponding to the nuclear resonance while the electron resonance is being observed (i.e. absorption of energy by the electronic magnetic moments from the alternating field). The interaction between the nuclear and electronic magnetic moments results in a modification of the electron-resonance signal which can be detected experimentally. Consequently, by varying the frequency of the alternating field in the region of the nuclear Larmor precession frequency we can determine certain nuclear resonant frequencies of interest, using the electron-resonance signal as an indicator. In so far as the effect under investigation is governed by the interaction between the nuclear and electronic magnetic moments, it is also possible to reveal in this way the nature of the electronic motion in the sample. Feher has made such experiments, which enabled him to determine with great precision the electron-density distribution in a paramagnetic crystal.

We have collected here only a few applications of nuclear magnetic resonance to the study of the structure of matter. Nevertheless, even from the examples described above, it is apparent that this method has great possibilities. There is little doubt that the nuclear-magnetic-resonance spectrometer will become as familar in our laboratories as the ordinary optical spectrometer is now.

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