INTERNATIONAL CONFERENCE on MAGNETISM

A Report by ***B. Dreyfus***

ABOUT two hundred participants, of whom three quarters came from abroad, were present at the International Conference on Magnetism that was held July 2–6, 1958, at Grenoble, France. The presence of delegates from 19 different countries, numerically well distributed, gave this meeting a truly international character. At Strasbourg (1939) and Grenoble (1950) the numbers of papers presented were 25 and 50, respectively; in 1958 there were 78 papers, taking in all 30 hours of meeting time. As purely technical papers were excluded, a high scientific level was ensured.

During the conference visits to Prof. Néel's laboratories and to the Centre d'Etudes Nucléaires de Grenoble were organized. The swimming-pool reactor of this research center went critical for the first time on July 2nd.

Five invited papers gave general reviews of recent work in various countries: Nagamiya (Japan), Montalenti (Italy), Vonsovskij (USSR), Casimir (Philips, Netherlands), and Valenta (Czechoslovakia). In this way the participants obtained a rapid general survey of these very interesting and sometimes little-known investigations. It will not be possible, in this article, to give a complete discussion of all the papers read, as they themselves are already condensed summaries; we will point out certain aspects only, and indicate the authors who presented the results.

B. Dreyfus, who served as chairman of the International Conference on Magnetism, is at the Institut Fourier, Grenoble, France.

IN recent years no such spectacular progress (as, for instance, has been seen in the field of superconductivity) has been made in the fundamental problems of ferromagnetism, although some interesting developments have been added. Van Vleck, in an invited paper, discussed the spin waves in the Heisenberg model, and insisted on the validity of linearization (Dyson) and on the extension to antiferro- and ferrimagnetics (the $T^{3/2}$ law demonstrated for the first time in ferrites by Kouvel). The latter question was also discussed by Szczeniowski. Danan investigated the approach to magnetic saturation of pure annealed polycrystalline Fe and Ni, showing that a $^{1}/_{H}$ term is not needed and that the results agree well with Holstein and Primakoff's formula, based on a spin-wave treatment. The coefficient of the $T^{3/2}$ law for the magnetization in Ni-Cu alloys has been measured by Kondorskij, et al. Kittel discussed the interaction between "magnons" (quantized spin waves) and phonons. Because of the different dispersion laws, magnons and phonons exist with the same frequency and the same wavelength. These have a very strong interaction, giving the possibility of ultrasonic resonance absorption, or, on the contrary, magnetic excitation of ultrasonic waves. Related questions have also received much attention from the Soviet physicists. Vonsovskij gave a general review of some theories of interactions between excited states: between phonons and magnons, between magnons and electrons for ferromagnetic resonance and electrical resistivity, in ferro- and antiferromagnetic metals and semiconductors, etc. These questions were also examined close to the Curie point by the "energy center of gravity" method.

For the collective electron model, Edwards and Wohlfarth showed that the inclusion of electron correlation, using the methods of plasma theory, leads to excited states having a spin-wave character.

New light has been shed on the problem of the electronic states responsible for ferromagnetism by measurements of the hyperfine coupling using the T^{-2} term of anomalous specific heat at low temperature (Kurti). The results for Co alloys and Tb show that there can be no appreciable *s*-electron polarization, as that would give a large hyperfine coupling. The influence of the crystalline symmetry on the "*d*" term is also clearly observed.

Kondorskij and Sedov have measured the influence of hydrostatic pressure and strong fields on the saturation magnetization and the resistivity of Fe-Ni alloys near 0°K. A detailed analysis of the results shows that σ_0 varies with pressure and field even at $T = 0°K$, which is incompatible with a simple Heisenberg model. The variation of resistivity also indicates a change in the electronic structure of the metal.

Vonsovskij also presented an experimental investigation of the coefficients of the thermodynamic potential near the Curie point, for a large number of substances.

A large part of Van Vleck's paper was concerned with the anisotropy in the Heisenberg model. Two classical models for the variation of K_1 in cubic substances were discussed: an octopolar potential (monatomic case) and quadrupole-quadrupole coupling ("anisotropic exchange") between two atoms. Due to spin correlation, both models lead to the same $(T/T_c)^{-10}$ law, at least for low temperatures. The problem of the anisotropy of ferrites was also briefly reviewed, with particular reference to Co.

THE magnetic properties of the alloys of the transition metals were treated in a large number of papers. Blandin and Friedel gave a theory of the long-distance interactions between atoms of these metals dissolved in low concentration in the noble metals. They first examined the influence of the exchange forces between the electrons localized in the neighborhood of an impurity ("virtual bound state"), and deduced a sort of generalization of Hund's rule, valid for atoms dissolved in a conducting matrix. Depending on the values of various parameters (width of the virtual bound states, Fermi energy, . . .) one finds complete (S_{max}), partial, or no uncoupling of the spins. The theoretical predictions agree well with the paramagnetic properties observed at low temperatures on a large number of alloys (Pauli-type paramagnetism if there is no uncoupling, etc.). The calculation of the interaction between two impurity atoms leads to a law in $J\ \vec{S}_1\vec{S}_2$, where J is a not too rapidly oscillating decreasing function. J has equal probabilities of being positive or negative, giving a sort of "antiferromagnetism" at low concentration. For higher concentrations, J is positive for the first neighbors, and we have a gradual transition to ferromagnetism.

On the experimental side, we mention Crangle's measurements on Pt_3Fe, which are antiferromagnetic in the ordered state and become ferromagnetic if the Fe content is decreased; Meyer's very exhaustive study of the intermetallic compounds of the Au-Mn system, which also shows ferromagnetism at low Mn concentrations; Kouvel, Graham, and Jacob's measurements of the magnetic properties of alloys close to Ni_3Mn in fields up to 10^5 oersted; Henry; Burger, Wendling, and Wucher; De Vries; etc.

DOMAIN theory and related problems received much attention. Néel considered two coupled square-loop domains. The curious hysteresis loops obtained in this simplified model give an explanation for the experimental fact that a hysteresis loop does not "close". Néel calls this phenomenon "tilting" (bascule). A second nonclosure effect occurs in real materials, as macroscopically similar states may be microscopically different. The coupling between domains gives a statistically fluctuating field, and Néel showed that in asymmetric loops the magnetization of the *n*th cycle will increase proportionally to $(\log n)^{\frac{1}{2}}$. This *reptation* * has been studied by Nguyen Van Dang for many materials, up to $n = 10^5$, and his results are in excellent agreement with Néel's theory, in spite of the great complexity of the phenomena. Bonnet, Dautreppe, and Gariod presented an electronic "reptograph", for rapid measurements of "tilting" and "reptation". Montalenti, Biorci, Ferro, and Pescetti read papers concerning the Preisach diagram representation, in particular on the determination of the domain distribution function $\phi(a, b)$ from the initial magnetization curve and the upper curve of the hysteresis loop, and on the irreversible phenomena related to the magnetization.

Artman and Foner gave a complete mathematical analysis of the magnetization processes (rotation and wall displacement) for a cubic crystal with superposed uniaxial anisotropy for various directions of the applied field. Their results agree well with measurements on a cobalt ferrite sample.

By his measurements of the magnetic field in spherical cavities in a magnetized rod, Meiklejohn indirectly demonstrated the existence of closure domains up to high values of the field, in agreement with Néel's predictions on the important role of impurities in the law of approach to saturation.

The problem of deducing the existence and the nucleation of domains from first principles was treated by Brown. He considered various approaches to this problem, and treated the case of an ellipsoid with randomly distributed impurities. Shtrikman and Treves gave a similar analysis of the nucleation of magnetization reversal in an infinite cylinder in a uniform field. We wish to mention, without going into details, the valuable in-

* We propose "crawling" as a possible translation of the French word "reptation"; "creep" gives the impression of a time-dependent aftereffect, while here we have dependence on *n* only.

formation obtained by Bates and Clow on thermomagnetic effects in very low fields, and Street's work using the change in Young's modulus (ΔE effect) to detect antiferromagnetic transitions in Cu-Mn alloys. It should be noted that no such transition is observed in Pd by this method.

Direct observations of domain walls were presented by Lee, who detected the position of a weakly oscillating wall in a toroidal perminvar specimen by means of a light probe (Kerr effect). Šur, using powder patterns, showed that the nuclei of magnetization reversal originate as closure domains, and also gave results on single domain particles and thermal and mechanical hysteresis.

SEVERAL papers discussed single domain particles. Wohlfarth has calculated the remanence for various types of anisotropy. Henning and Vogt have studied the colloidal solutions of Fe and Co in Hg. By heat treatments they can modify the grain size distribution, which is measured by Weil's method, using the "quasi-paramagnetic" and "ferromagnetic" states. The measurements of magnetization agree with Klein and Smith's theory. In the same field we note the measurements of the coercive force of ferromagnetic precipitates in Cu and Au, by Sucksmith at room temperature, and by Weil at very low temperatures, as well as measurements by Bean, Livingston, and Rodbell. The latter authors studied the anisotropy and the remanence of cobalt grains in a copper monocrystal, with the rather surprising result that the anisotropy of the atoms on the grain surface is the same as in the interior.

Colombani, Goureaux, and Huet have measured the electrical resistivity and Hall effect of thin films of Ni: they determine the Curie point and estimate the magnetization, and compare these with the various theories, without arriving at conclusive results. Weil and Conte studied thin films of Fe and Ni, evaporated on supports held at temperatures from 4°K upwards. On heating, a certain structural rearrangement already takes place below 20°K.

Fuller presented beautiful photographs of powder patterns on thin films of Fe-Ni alloy evaporated in a field, showing the different wall movements for a field applied parallel or perpendicular to the anisotropy axis.

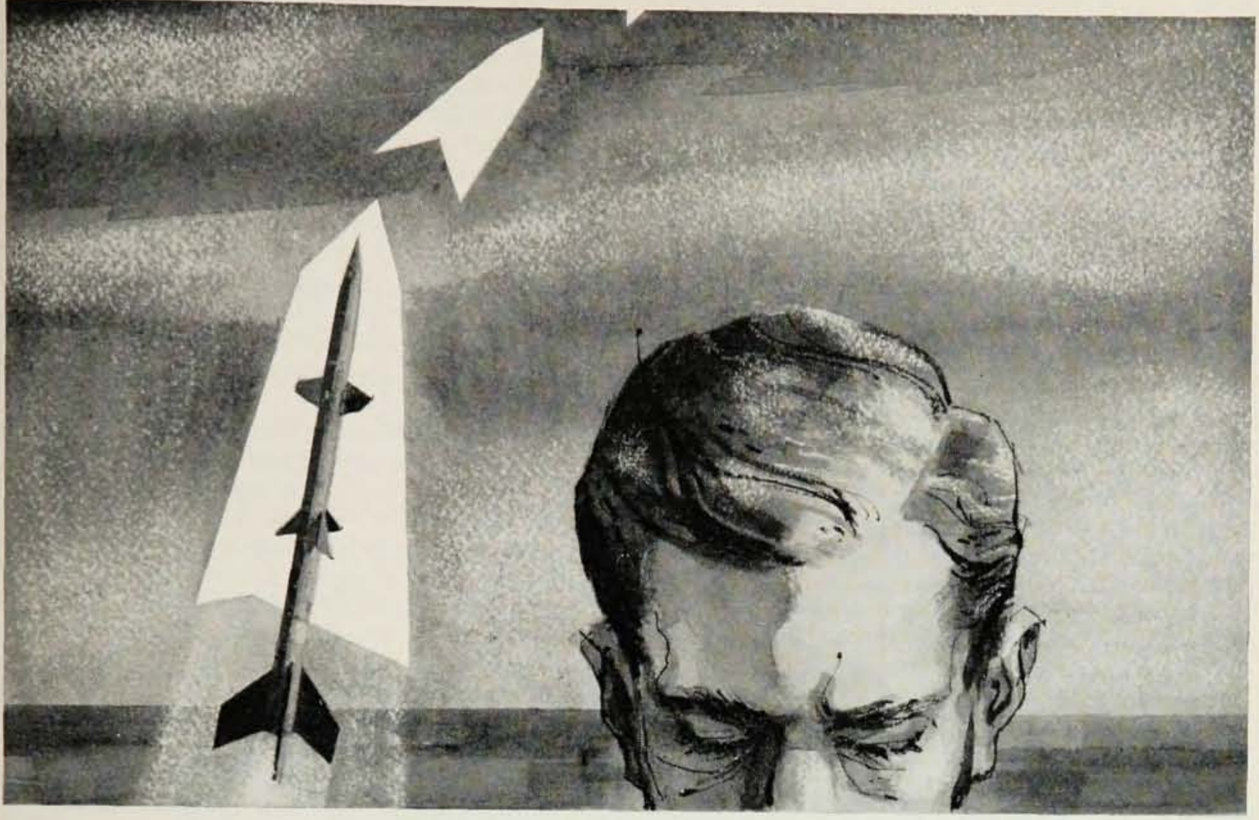
IN 1950, Néel presented his theories of the magnetic after-effect, which has been widely investigated since. Some very delicate work by Brissonneau clearly demonstrates the concept of the "aftereffect field" for diffusion of C in Fe, and the proportionality of this field to the concentration of dissolved carbon: this very sensitive method also gives a value for the solubility limit. Bosman, Brommer, and Rathenau studied Fe-Si alloys, for which the magnetostriction changes sign with the concentration, and show that there is no correlation between the after-effect and the magnetostriction, in agreement with Néel's theory. After-effect measurements using C^{13} give a value for the isotope effect agreeing with that expected for thermal agitation. The activation energy for diffusion of H, C, and N in various elements and alloys has been calculated (Montalenti) by a simple elastic model, and gives good results. Kawai and Kume studied the fluctuation after-effect by measuring the magnetization vector of geological samples for time periods of up to 10^7 years.

In 1954, Néel published a theory of anisotropic distributions of nearest-neighbor links in binary alloys, induced by heat treatment ("directional ordering"). Two workers in Grenoble are studying this experimentally. Ferguson has measured the uniaxial anisotropy induced in Fe-Ni and Fe-Co alloys by a heat treatment in a magnetic field, and has found interesting interference effects of directional and normal ordering. Vergne used the displacement of the magnetization curve to measure the uniaxial anisotropy induced in a stressed Fe-Ni wire by a heat treatment, and finds good agreement with theory. Kienlin, Kornetzki, and Rabl annealed perminvar-type ferrites in weak fields, and observed large changes in the hysteresis loops.

NEUTRON diffraction, still in its infancy at the 1950 conference, is now a well-known tool. Single crystal results often show that structures are more complicated than was expected from powder sample measurements. In an invited paper, Shull reviewed some recent developments in the determination of magnetic structures, in particular Hamilton's work on ionic ordering in Fe_3O_4 at low temperatures, and Roth's measurements on the monoxides of transition metals. The use of polarized neutrons has greatly increased the precision of the measured magnetic structure factors, for instance in Fe and Ni. Koehler, Wilkinson, Cable, and Wollan described their measurements on monocrystals of antiferromagnetic halides of the transition elements at liquid helium temperatures. The influence of a very strong field on $FeCl_2$, and the newly determined magnetic layer structure and antiferromagnetic domains of $MnBr_2$ are of particular interest.

The problem of spatial correlation of spins above the Néel temperature in CoO has been studied by McReynolds and Riste. The results can be interpreted by extension of the molecular field method. Ericson and Jacrot have studied the spin correlations in time, for Fe near the Curie point. The line shapes observed give results which seem to agree with a Heisenberg model.

SEVERAL interesting papers were presented on the ferrimagnetic rare earth garnets, which have only fairly recently been discovered but have already been widely investigated. Pauthenet showed that in various Gd garnets the magnetization of the Gd^{3+} ions follows the same Brillouin curve ($J = 7/2$). As the field acting on an ion depends on the molecular field coefficients, this gives a further confirmation of the usefulness of the molecular field hypothesis. On the other hand, for the ions with an orbital moment (Dy^{3+}, Er^{3+},



Yb^{3+}) the low-temperature point demonstrates the existence of quenching of orbital moment. Cohen and Ducloz have made systematic measurements on paramagnetic gallates and garnets, and their $1/\chi\ (T)$ curves show a typical curvature due to the gradual quenching of the orbital moments, in excellent agreement with Ayant and Thomas's calculations, which were made using the hypothesis of a mainly cubical crystal field.

The susceptibilities of the rare earth garnets have been measured by Aléonard and Barbier from the Curie point up to 1600°K. From the results they deduce the values of the molecular field coefficients, which agree with Pauthenet's values obtained in the ferrimagnetic region. Volkov and Čečernikov have done similar work on ferrites. We also mention a systematic investigation of the Al-, Ga-, and Cr-substituted ferrite garnets, which fits in well with the existing theories (Villers, Pauthenet, and Loriers); experimental work on Al-, Ga-, and Cr-substituted Ba hexaferrites by Bertaut, Deschamps, Pauthenet, and Pickart, and a large number of investigations on various compounds by Bozorth and Kramer, and the Japanese work reviewed by Nagamiya.

The tetragonal distortion of the octahedron of anions surrounding a Mn^{3+} ($3d^4$) ion can explain some magnetic and structural properties of some Mn compounds (Goodenough). Above a certain critical concentration on the octahedral sites this distortion is cooperative and macroscopically visible. It is also responsible for three types of indirect interaction between Mn^{3+} ions, two being antiferromagnetic, and for explaining the properties of certain compounds.

Active research is being carried out on antiferromagnetism, both with neutrons and by simpler means, with often equally valuable results. We cannot enter into details, and apart from Bozorth's and Kouvel's papers, we can only mention Bizette, Terrier, and Tsai's measurements on cobalt halides, and McGuire and Happel's results on MnO. The influence of a mechanical stress on a NiO single crystal during cooling through the Néel point clarifies the domain structure of this antiferromagnetic substance (Nagamiya).

IN 1950, ferromagnetic resonance was only treated in a review paper by Kittel; in 1958 seven communications were presented in this field. Ferrites and garnets have been studied, in particular near the compensation temperature (exchange resonance), on polycrystals by Paulevé, Dreyfus, and Soutif, and on monocrystals by Geschwind, Walker, and Linn. Schlömann's paper treated the resonance line width in polycrystals. He distinguishes two limiting cases, according to whether the anisotropy field is small or large compared with the dipolar interaction between the grains. In the strong-coupling case the broadening is due to the interaction between the resonance mode and the "magnetostatic" modes, and, in the limit, with the classical spin waves.

Foner has used pulsed fields up to 750 kilooersted in a wide temperature range. This enormous increase of field makes new problems accessible with the available frequencies, in particular antiferromagnetic and ferrimagnetic resonance, and gives valuable information on the "molecular field". The pulsed field technique is also promising in paramagnetic resonance.

In their work on metallic thin films, Tannenwald and Seavey measure the magnetization by using Kittel's formula. Problems of spin dynamics (exchange effects, skin effect, harmonic generation) are also treated. An interesting original method for detecting resonance is proposed, based on the appearance of a dc voltage in the film. The origin of this voltage is not yet clear (Hall effect?). Asch's measurements on $MnAu_2$ enable him to determine the molecular field coefficients and the anisotropy constants.

Owen has studied the antiferromagnetic coupling in iridium salts by the paramagnetic resonance of pairs of nearest neighbor Ir ions in a somewhat diluted (1/20) crystal; the intensity variation with temperature gives the distance between the singlet (fundamental) and the triplet whose resonance is studied. The value of the exchange integral thus obtained agrees with that found from the Curie-Weiss law of the concentrated crystal. One also finds an upper limit to the second-nearest neighbor interaction.

The nuclear resonance of F^{19} in MnF_2 enabled Jaccarino and Walker to determine accurately the magnetization of each sublattice as a function of T. At very low temperatures, the law is exponential, which proves the existence of a forbidden band in the spin-wave spectrum. This is to be compared to the classically expected T^3 law and the T^4 law found on $CuCl_2 \cdot 2H_2O$ by Gorter and Poulis. The relaxation time has been measured and is abnormally short. Suhl gives a theory of nuclear line broadening in magnetic substances, by calculating the second-order hyperfine coupling with spin waves.

AS for the optical properties of magnetic substances, Krinčik observed two resonances in the visible region on Fe, Ni, and Co. One is attributed to $3d$-$4s$ transitions, the other, tentatively, to a spin reversal in the exchange field.

Dillon gives results on the absorption, rotation, and dichroism of light passing through a thin layer of a ferrimagnetic garnet. Various transitions are observed, and attributed to electronic transitions of Fe^{3+} on octahedral sites. Clogston gives a more detailed theory of this effect. He attributes the 20 000 cm^{-1} line to the transition from the fundamental state of Fe^{3+}, ^6S, to ^6P, while the absorption around 16 000 cm^{-1} is attributed to a dipolar ^6S-^4G transition, which becomes possible by a coupling of this state with the states of higher energy, caused by crystalline fields related to thermal waves.

Violet absorption measurements at very low temperature on $MnCl_2 \cdot 4H_2O$ and $MnBr_2 \cdot 4H_2O$ have been made by Tsujikawa and Kanda. The appearance of antiferromagnetism shows itself by a line shift and a change in relative intensity.