Lorentz-Kamerlingh Onnes Centenary Conference on Electron Physics in Leiden[1]

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IT IS A CENTURY this year since the Dutch physicists, H. A. Lorentz and H. Kamerlingh Onnes, were born. Lorentz is famous as the first to give classical explanations of electromagnetic and optical properties of matter by his theory of electrons, which also led him to the discovery of the Lorentz transformation, a discovery which later gained new significance from Einstein's theory of relativity. Kamerlingh Onnes, the first to liquefy helium, is famous for the discovery of superconductivity, a phenomenon which still offers unsolved problems to theoretical physics.

In commemoration of this double centenary, the University of Leiden (Netherlands) organized a Lorentz-Kamerlingh Onnes Conference on electron physics, which was held on June 22–27, 1953. The invited participants came from 13 countries: *Belgium* (Van Itterbeek), *Canada* (MacDonald), *Denmark* (Bohr), *France* (Proca), *Germany* (Heisenberg), *Great Britain* (Dirac, Fröhlich, Mendelssohn, Peierls, Pippard, Rosenfeld, Shoenberg, Simon), *Italy* (Ferretti), *Japan* (Tomonaga), *Netherlands* (DeBoer, Broer, Casimir, Druyvesteyn, Fokker, Gorter, Groenewold, De Groot, De Haas, Van den Handel, Jonker, Korringa, Kronig, Nijboer, Rathenau, Sizoo, Wouthuysen, Zernike), *Norway* (Wergeland), *Sweden* (Borelius, Källen), *Switzerland* (Fierz, Pauli), *U.S.A.* (Belinfante, Bloch, Daunt, Lamb, London, Pais, Squire). The meetings took place in the famous Kamerlingh Onnes Laboratorium in Leiden, where the first liquefaction of helium took place, where record low temperatures have been reached, and where the Zeeman effect was discovered. The foreign participants were guests of Leiden University in a hotel on the beach at Noordwijk aan Zee, which greatly helped create the congenial atmosphere that marked the conference.

The subject of the meeting was confined to the properties of conductors at low temperatures, and a discussion of the present status of quantum field theory, in particular of electrons.

The meeting was opened on Monday, June 22, by the President of the Board of Trustees of the University, Dr. De Vos van Steenwijk, who announced that (subject to Parliament approval) the Dutch government had founded a "Lorentz chair for theoretical physics" at Leiden for foreign visiting professors to be invited for a stay of one year.

[1] The proceedings of this conference will appear in a special issue of *Physica* in the near future.

Electrons in Metals at Low Temperatures. The scientific proceedings were opened by a brief review of existing knowledge of superconductivity by C. J. Gorter (Leiden). One may study (1) the properties of superconductors at 0° K, (2) the temperature dependence of properties of superconductors, and (3) the properties of actual samples, in which there may be mixtures of normal and superconducting regions.

1) Except for a difference in magnetic energy between the n(ormal) and the s(uperconducting) states when the sample is placed in a field, the internal energies of the n and the s state are equal to each other when in equilibrium. The difference ΔU_0 due to magnetic energy is much less than RT_c, if T_c is the transition temperature. It is also inversely proportional to the average atomic weight, as has been found by study of isotope mixtures of a few metals such as tin or thallium. This isotope effect has been explained by Fröhlich and Bardeen, who also explained why particularly metals, which, notwithstanding a high density of valency electrons, have a high resistivity at high temperatures, are likely to become superconductive.

In superconductors, by acceleration of the frictionless conduction electrons, the electric field $\mathbf{E}$ is proportional to $d\mathbf{J}/dt$ instead of to the current density $\mathbf{J}$. Currents follow the surface of the material, in a thin surface layer of thickness l (penetration depth). According to the London equation, curl $\mathbf{J}$ is proportional to $\mathbf{B}$, and the boundary conditions are such that the average (kinetic + potential) momentum of the electrons may be considered a constant throughout the superconductor in a stationary s state. (In the n state, the average *kinetic* momentum vanishes.) The London equation is a phenomenological equation; according to Pippard, it is not rigorously valid in regions of rapid variation of the magnetic field.

2) The thermodynamic properties of superconductors may be explained by equating the electronic part of the Helmholtz free energy F of the sample to $\Delta U_0 - \frac{1}{2}\gamma T^2$ in the normal state (to which a magnetic field energy $H^2V/8\pi$ is to be added in a magnetic field), and to $x\Delta U_0 - \frac{1}{2}x^{\frac{1}{2}}\gamma T^2$ for the superconducting state (no additions in a field), where x in some way measures the fraction of electrons that are in the normal state. At $T=0$ one has $x=0$; at the transition point T_c in zero field the last remainder of superconducting electrons disappears ($x \rightarrow 1$). Below T_c there is a mixture of s and n electrons; the value of x is

found by minimizing F for the superconducting state as a function of x. The transition curve between n and s state is found by equating $F_n - F_s$ to $H^2V/4\pi$; one thus obtains for the threshold field $H_t = H_{t0} \times (1 - T^2/T_c^2)$ with $T_c = 2(\Delta U_0/\gamma)^{\frac{1}{2}}$ and with $\Delta U_0 = H_{t0}^2V/8\pi$. Also $x = (T/T_c)^4$ independent of the field H. From F one obtains for the electronic part of the specific heat the value γT in the n state, and $3\gamma T^3/T_c^2$ in the s state, so that at the transition point T_c the electronic specific heat in the s state is three times larger than in the n state. To this, the Debye specific heat of the lattice is to be added.

Fundamental lengths entering the discussion of superconductivity are, besides l, also the mean free path of electrons (λ), the depth of a possible skin effect, and in Pippard's theory the "range of coherence."

Superconducting electrons seem rather decoupled from the heat motion of crystalline matter (as seen from thermoelectric properties and thermal conductivity), contrary to the assumptions of Fröhlich and Bardeen.

3) In actual samples, the state of affairs usually is more complicated. Demagnetization factors must be taken into account. There is no longer a sharp transition (for fixed temperature) at one threshold field, but there is an intermediate region in which the field starts to penetrate the sample.

The discussion was started by Simon (Oxford), who reported on measurements of superconductivity under high pressure. For instance, bismuth becomes superconductive with a transition point of 7° K between 20,000 and 40,000 atmospheres. This is probably due to a modification of the crystal, and not a mere volume effect. By comparing the isotope effect and the pressure effect, one can single out the effect which a change of volume alone may be expected to have.

Fröhlich (Liverpool) asked how well the M^{-1} law for the isotope effect and the T^3 law for C_v in the s state were experimentally justified. Gorter reported deviations from the T^3 law for niobium; this was also to be expected according to the theory of Heisenberg and Koppe. For mercury, on the other hand, the T^3 law is valid, contrary to this theory.

Casimir (Philips Lab., Eindhoven) justified the formula given for F in terms of x. He assumed that the order parameter x was proportional to the *square* of the fraction of the surface of the Fermi sphere which had gone over into the n state; the term $x\Delta U_0$ was then to be interpreted as an interaction between pairs of n electrons. The main reason for choosing this particular dependence of F on x lies in the fact that this assumption leads to such surprisingly good agreement of its consequences with experiment.

Pippard, Lamb, Bloch, Heisenberg, Mendelssohn, London, and Peierls also took part in the discussion.

K. Mendelssohn (Oxford) reported on the thermal conductivity K of superconductors. In pure metals, $K_s < K_n$. This must be due to less thermal conductivity by electrons in the s state than in the n state. ($K_{es} < K_{en}$). For alloys K_s <or> K_n. If $K_s > K_n$, this must be due to more thermal conduction by the lattice, caused by the s electrons' loss of ability to scatter phonons. The temperature dependence of K_s is often peculiar; the sign of $K_s - K_n$ may change from + to − or from − to + at a temperature below T_c. The thermal resistivity $1/K$ may contain a term $\propto T^2$ representing lattice scattering, and a term $\propto T^{-1}$ representing impurity scattering. Whether the one term or the other is predominant, also depends strongly on the concentration of small admixtures of other metals. At very low temperatures (below 1° K), however, K_n becomes simply proportional to T and K_s, some 1000 times smaller, follows a T^3 law. This large difference between K_s and K_n can be used for making a "thermal switch" which gives thermal contact in the n state and breaks the contact in the s state. This may for instance be used in cooling techniques.

Columbium behaved peculiarly when the s state was destroyed by a transverse magnetic field. As usual, the thermal resistivity $1/K$ started to change at half the threshold field H_c, and obtained its low n value at $H = H_c$. However, instead of a gradual drop of $1/K$ from $1/K_s$ to $1/K_n$, there was a pronounced *maximum* of $1/K$ between $H = \frac{1}{2}H_c$ and $H = H_c$. This effect has not been explained.

Bloch, Peierls, Pippard, Casimir, Shoenberg, Daunt, and Gorter took part in the discussion.

In the afternoon, A. B. Pippard (Cambridge) reported on his theory of coherence in superconductors. This is a qualitative rather than a quantitative concept. In terms of the order parameter x, or the quantity $\omega = 1 - x$, it may be expressed by saying that ω cannot change rapidly with position over distances smaller than about 10^{-4} cm. One way of explaining this fact is imagining that s electrons would evaporate into an n region if the boundary between s and n regions is initially sharp. This makes the boundary fuzzy. This coherence might be reduced by reducing the mean free path of the electrons, such as by mixing 3 per cent of indium homogeneously into pure tin, which makes λ and the coherence range much less than 10^{-4} cm. Coherence directly affects the interphase surface energy between s and n regions. Doidge has found experimental evidence for this.

Another consequence of the coherence concept is the necessity to alter the London equation. Tentatively, Pippard suggested that the vector potential $\mathbf{A}$ in the equation $\Lambda\mathbf{J} + \mathbf{A} = 0$ be replaced by $(3/4\pi\xi_0) \iiint \mathbf{r} (\mathbf{r} \cdot \mathbf{A}) \exp(-r/\xi) r^{-4}\, dxdydz$. Here ξ measures the coherence range and ξ_0 is characteristic of the metal but independent of impurities.

In the discussion, London (Duke University) suggested the replacement of $\mathbf{J}$ by curl $\mathbf{J}$ and $\mathbf{A}$ by $\mathbf{B}$ in Pippard's equation, for the purpose of gauge invariance, important for application of the formula to rings. A similar equation might then be valid with $\mathbf{J}$ replaced by $\partial\mathbf{J}/\partial t$ and $\mathbf{A}$ by $-\mathbf{E}$. Fierz, Fröhlich, Peierls, Mendelssohn, Bloch, MacDonald, Van Itterbeek, and Casimir also took part in the discussions.

Squire (Rice Institute) reported briefly on an experiment on the alteration of the transition curve $H_c(T)$ by pressure or tension of the sample.

The discussions on electrons in metals were continued on Thursday, June 25.

H. Fröhlich (Liverpool) started the morning session with the discussion of superconductivity and lattice vibrations. The interaction between electrons and lattice vibrations, which is responsible for the resistivity at high temperatures, forms the basis for a field theory and thus leads to a self-energy of the electrons. Part of this energy simply leads to a renormalization of the velocity of sound. The self-energy, however, becomes important near the top of the Fermi level. As a consequence, a state deviating from the Fermi distribution will be stable (and is identified with the superconducting state), if the resistivity at high temperatures is large, notwithstanding a large number of conducting electrons. It can then be shown by a crude calculation that the energy of a superconductor will be inversely proportional to its molecular weight. This "isotope effect" has been verified experimentally. Fröhlich then showed that methods based on a one-particle approach are inadequate to deal with the mathematical problem, and that new methods should be developed in order to find a satisfactory theory of superconductivity.

Bohr, Peierls, Bloch, Casimir, Heisenberg, Shoenberg, London, and Kronig took part in the discussion. The inadequacy of the one-particle approach was in particular stressed by Bohr (Copenhagen). Typical for the superconducting state is the disappearance of the scattering of electrons by impurities. Peierls (Birmingham) agreed; the sharpness of the transition point alone shows that a pure one-electron method cannot work. But neither Fröhlich's theory nor the theory of Heisenberg-Koppe is purely a one-electron method. One-particle states are used merely as building stones for a cooperative state.

Bloch (Stanford University) thought one should first show that macroscopic diamagnetism is established. Others thought it was more important first to show that stable states are possible where there is a current at 0° K. Some remarked that a satisfactory solution of this problem might be expected only after someone's ingenious guess what this stable distribution will really look like. Heisenberg (Göttingen) agreed with Casimir (Philips Laboratory, Eindhoven) that the coupling with the lattice vibrations proposed by Fröhlich probably was more important for the establishing of a superconductive state, than the Coulomb interaction of the Heisenberg-Koppe theory. The smallness of the entropy in the superconductive state shows almost complete order in configuration as well as in momentum space. One may have to guess at this ordered state as one may guess the shape of a crystal lattice. Shoenberg (Cambridge) argued that the discrepancy by a factor 3 between the number of conducting electrons as found from the constant Λ in London's theory, and as present in the normal conducting state, is an indication that Fröhlich's distribution with electrons on a separate shell in momentum space separated from the Fermi contribution probably comes closer to reality than a displaced Fermi contribution. The transition temperature is very sensitive to pressure. Is this due to a pressure dependence of the electron velocities? Fröhlich remarked that it was difficult to say with certainty what the actual distribution in momentum space is in the superconductive state. The separated shell had not been what he was looking for, but had been the best he had as yet found.

D. Shoenberg (Cambridge) discussed the De Haas-Van Alphen effect, that is, an oscillatory variation of magnetic susceptibility with field at low temperatures, first discovered in 1930 for bismuth, and explained theoretically by Landau. The unusual effective masses to be used in the theoretical formula for fitting the experimental data may be justified by the unusual curvatures of the Fermi surface where it crosses Brillouin zone boundaries. With improved experimental techniques, in which peak magnetic fields of 100,000 gauss were instantaneously obtained, measurements have been made of the effect in tin and in lead.

Peierls and De Haas took part in the ensuing discussion.

On Thursday afternoon, J. Korringa (Leiden) opened the session by giving a survey of his theoretical explanation of the experiments of Gerritsen on the low-temperature resistance of dilute alloys, in particular gold, silver, or copper, with paramagnetic ions (Mn, Cr) as a solute. The essential point in this theory is that the scattering of the conduction electrons consists for a considerable part of a spin-dependent "rearrangement scattering," which has a resonance energy lying very close to the Fermi level. The model which gives rise to such a scattering is incompatible with the usual one-electron approximation.

Simon, London, Gorter, Kronig, and Fröhlich took part in the discussion which followed.

G. Borelius (Stockholm) gave a survey of some old and some new measurements of the thermoelectricity of metals at low temperatures. He pointed to the frequent deviations from the theoretical expectations for pure metals and stressed the importance of combining resistance measurements of dilute alloys with measurements of the absolute thermoelectric power. Pippard, Mendelssohn, Korringa, and Gorter took part in the discussion.

D. K. C. MacDonald (Ottawa) concluded the afternoon session by a report on his measurements of the thermoelectric power of dilute alloys and their implications for the underlying electronic structure. His conclusions gave a further confirmation of the model introduced by Korringa and Gerritsen, pointing to a strong variation of the collision time in the neighborhood of the Fermi level.

On Friday afternoon, F. London (Duke University) surveyed the theory of superconductivity. In the old days, it was believed that quantum theory was "bottled up" in atoms and molecules. One also needed quantum mechanics for finding the Brillouin zones for electrons in metals; but these were largely used only as a modification of the energy of electrons in terms of momentum, and further calculations with this modified energy were then performed classically.

The existence of superconductivity has shown that this is all too simple. Superconductivity, and superfluidity in helium, are macroscopically large quantum mechanisms, for fermions and bosons respectively. One has here a case where Δp in the uncertainty relation $\Delta p \cdot \Delta q > \hbar$ is very small; therefore, Δq is large here.

Together with his brother, Fritz London had expressed the Meissner effect by curl $\mathbf{J}_s = -(n_s e^2/mc)\mathbf{B}$, which was, on account of boundary conditions, essentially equivalent to making the average total (= kinetic + potential) momentum of superconductive electrons equal to zero. Besides the superconductive current density $\mathbf{J}_s$, there can be a normal current with $\mathbf{J}_n = \sigma\mathbf{E}$, as shown by Joule heat developed by fast oscillating fields applied to superconductors by his brother.

The London theory of superconductivity is often called a phenomenologic theory. In fact it goes beyond that. It shows that in a superconductor the average momentum is frozen in and stays zero as a magnetic field is switched on. (In the normal state, it is only the average *kinetic* momentum that is frozen in.) The long-range order in p suggests a quantum-mechanical feature. While the order in a ferromagnet says that the spin of one atom here equals the spin of a different atom somewhere else, the order in a superconductor says that the electron momentum here equals the electron momentum somewhere else, but it may be the same electron, of unspecified position. The electron state at absolute zero is not degenerate here, in contrast to the ground state of a ferromagnet.

Fröhlich and Bardeen think that superconductivity is due to the interaction of electrons and the lattice phonons. The interaction may best be described in momentum space.

Pippard's experiments have suggested the introduction of the idea of coherence as a refinement of the London theory. This idea is closely analogous to the idea of a mean free path, and it explains the effect of impurities. However, this idea greatly complicates the simple formulas, and therefore London is reluctant to accept this return to the spirit of classical physics incorporated in the mean free path idea, as long as there are no further experiments showing the need of such change in the theory.

Both superconductivity and superfluidity make use of a typical two-fluid model. For temperatures below a certain transition point, the system splits up into two subsystems, between which there is an equilibrium, and which penetrate each other in every volume element instead of separating into two phases. (They may be separated in momentum space.) The superconductive (superfluid) fluid has no entropy at all.

The supercurrent is maintained *not* by the *absence* of collisions but by the thermodynamic equilibrium state established just *by* the collisions, and its current distribution is determined by the applied magnetic field. In order to solve the mathematical problem of finding this stable state, one would need a new approach to many-body quantum-mechanical problems, some drastic but simple, workable idealization. The assumption of the existence of order in momentum space seems promising; it is kind of an analogon to the existence of order in *xyz*-space for a crystal.

Casimir (Philips Laboratory) added that at absolute zero superconductivity has three aspects: the diamagnetism, the existence of persistent currents, and the existence of two stable states at 0° K, namely, the normal state little dependent on the magnetic field, and the superconducting state of lower energy with electron velocities depending on the magnetic field. Different discussants stressed different ones of these three aspects, but all are important.

Quantum Electrodynamics. Tuesday, June 23, was dedicated to problems of quantum electrodynamics. H. B. G. Casimir (Philips Laboratory) opened the discussion with an introduction about the electromagnetic mass of the electron. After a brief review of the classical theories of Lorentz and Poincaré, he mentioned the quantum-mechanical self-energy of an electron, which is largely reduced by positon theory, and which is taken care of by mass renormalization. Modification of the electromagnetic mass of an electron when it is bound in an external field is observable, as in the Lamb shift. He closed his introduction by discussing an electron model consisting of a conducting charged spherical shell of unknown radius R. This sphere alters the boundary conditions for the electromagnetic field, and thus modifies the zero-point (fluctuation) energy of this field. The result of this is a force keeping the shell together, which may be balanced against the repulsive Coulomb forces. As the latter are proportional to e^2, and the fluctuation energy to $\hbar c$, such theory should also yield some value for $e^2/\hbar c$. Details had not yet been worked out; anyhow, the model seemed doubtful.

Pais, Rosenfeld, Peierls, Dirac, Fierz, Källen, Heisenberg, and Belinfante participated in the discussion of this model. Pais (Princeton) remarked that the Coulomb attraction energy did not have the classical value $\propto 1/r$ used by Casimir, but $\propto \log r$ on account of positon theory. Peierls (Birmingham) ventured that if one would also take into account the changes of boundary condition for the quantized electron wave function on the spherical shell, the effect of this would also make the resulting attraction energy logarithmic and still enable us to work out a theory of this kind.

F. J. Belinfante (Purdue University) gave a brief description of a method of avoiding the use of an infinite continuum of occupied states of negative energy and to formulate positon theory without use of the concept of "hole theory." The state vector in his theory is a product of a function antisymmetric in the positon coordinates, and one antisymmetric in the negaton coordinates. The operation of the quantized ψ-function on such state vector can be defined in such a way as to yield the usual anticommutation relations for ψ and ψ^*. All operators of hole theory, including those with matrix elements corresponding to pair creations and annihilations, can also be defined in this positon theory without holes. The possibility of such formulation of positon theory is very satisfactory, but for practical applications of the theory ordinary hole theory is at least just as convenient as this new formulation of positon theory.

G. Källen (Lund) discussed renormalization technique. The usual renormalizations of quantum electrodynamics can be formulated without use of series expansions in powers of e^2. The usual field equations are modified by addition of terms with unknown coefficients, which are chosen in such a way as to make the renormalized field variables satisfy the same commutation relations as the original variables. These constants are expressed in terms of certain integrals; observables are defined in terms of slightly different integrals. There are three possibilities: (*a*) Both of these groups of integrals converge. There are indications that this is not the case. (*b*) The integrals not of the former, but of the latter group, converge. Such theory is at least physically acceptable. (*c*) Everything diverges. One should then find a different way of solving the field equations. It is not yet definitely certain whether case (*b*) or case (*c*) is realized.

Peierls, Pais, and Heisenberg took part in the discussion of Källen's paper.

In the afternoon, L. Rosenfeld (Manchester) reported on some problems of interpretation of quantum electrodynamics. The classical theory contains no elements from which a form factor could be derived for the electron. Therefore, any results depending on the deviation of the electron from a point-charge model are arbitrary. Nonlocal quantum theories exhibit the same arbitrariness. Techniques of renormalization and regularization have been developed, which take care of the various infinities. This is a purely formal procedure, however. It is important to know the degree of approximation of the finite effects left after this procedure. This is given as an argument for expansion in powers of $\alpha = e^2/\hbar c$; such expansion around $\alpha = 0$ is probably impossible, however, and Thirring thinks expansions will not converge for any finite value of α. The only possible justification of the use of the semiconvergent expansions in powers of α is its correspondence to classical procedures. In order to obtain a result that is accurate in a definite order of approximation, radiative interaction through transverse photons should then be treated as a correction of order higher than the Coulomb interaction, contrary to what one finds by incorporating the purely fictitious longitudinal photons.

Attempts have been made to deal with problems by a relativistic generalization of perturbation theories. In quantum electrodynamics this does not give rise to particular problems. When applied to meson theory, however, a method proposed by Tamm and Dancoff has the disadvantage of not keeping the different orders of approximation separated, whereas it is doubtful whether the symbols introduced in the theory of Bethe and Salpeter have a well-defined meaning.

Källen, Peierls, Fierz, and Pais took part in the discussion of Rosenfeld's paper.

W. E. Lamb (Stanford University) presented the newest experimental and theoretical numerical values for the Lamb shifts of hydrogen, of deuterium, of ionized helium, and the $1^3S_1 - 1^1S_0$ separation of positonium. In the case of deuterium there seems to be a slight discrepancy between the experimental 1059.1 ± 0.1 Mc/sec, and the theoretical 1058.44. The discrepancy is comparable to that for hydrogen; but there is good agreement between the predicted *difference* in Lamb shift between deuterium and hydrogen (1.331 Mc/sec), and the experimental value for this difference (1.23 ± 0.14 Mc/sec). The theoretical values are accurate up to the 4th order. Further measurements of the Lamb shift, of the $n = 4$ state of He^+, the $n = 3$ state of H, and the 2^3P_J and 3^3P_J levels of He are planned. For a comparison of the latter with theory, good two-electron wave functions will be required.

F. Bloch (Stanford University) presented the latest results on the g-factor of the electron. There is a perfect agreement between theory and experiment; however, as the experimental error is comparable in magnitude with the second-order correction in the theoretical value, the experiment is not accurate enough for a definite verification of this correction. Also, for the valency electron in gallium the g-factor, found experimentally under the assumption that the orbital magnetic moment is not anomalous, is in agreement with the theoretical value for a free electron.

Bloch reported experiments by Crane and collaborators in Ann Arbor (Michigan), in which the magnetic moment of free electrons was measured by determining the rotation of the plane of spin polarization of a polarized beam of electrons in a longitudinal magnetic field. The electrons move in helical motion around and along the average direction of the beam. The slight deviation of the electron g-factor from 2 would, in the nonrelativistic approximation, cause a slight difference in the angle of rotation of spin polarization and of helical motion. However, for the 420-kv electrons used, relativistic corrections must be taken into account, in which the spread in kinetic energy of the electrons causes an error, so that no precision work has as yet been possible.

A different method of measuring the g-factor of free electrons will be used at Stanford University, using slow electrons which are trapped in a weak electric potential well of depth 10^{-5} volt with the help of a variable magnetic field. Only electrons in the lowest magnetic quantum state will be trapped. The trapped electrons in a magnetic field of about 10^3 gauss will then be subjected to an oscillatory field, and the number of induced transitions will be observed by the escape of the electrons from the trap. It is expected that in this way the g-factor can be measured with an accuracy of about 10^{-5}.

Kronig, Heisenberg, Pais, Fierz, Lamb, Gorter, and De Groot took part in the discussion.

New Theories. The last regular working session on Friday morning, June 26, was dedicated to some new ideas in field theory.

A. Pais (Institute for Advanced Study, Princeton, New Jersey) presented a new theory of heavy particles in interaction with mesons. The problem he had set himself to solve was the question whether one could simultaneously understand the theoretical importance of the isotopic spin, conservation laws of charge and of number of heavy particles (by which he understood mainly nucleons and V_1-particles), and the (meta)-stability of V_1-particles against decay into a nucleon by pion or by photon emission. The stability of the V_1-particle cannot be understood on the ground of theories of a nucleon isomer proposed by others.

If the isotopic spin is considered as more than just a label to indicate charge—if it is to be a real "spin"—then it must correspond to an intrinsic angular momentum ($\frac{1}{2}$ for nucleons) in a three-dimensional space, which Pais called the "ω-space." In this space provisionally only angles and rotations are defined and the distance from the origin has no meaning, so that ω-space may as well be regarded as a two-dimensional space with coordinates (ϑ, φ). The wave function of the nucleon is then defined as a function $\psi\ (x, y, z, t, \vartheta, \varphi)$ in six dimensions. It is a spinor with respect to rotations in (ϑ, φ)-space as well as in (x, y, z)-space. The nucleon may have an orbital angular momentum L_x, L_y, L_z in (x, y, z)-space, but also an orbital momentum (K_1, K_2, K_3) in ω-space. From the isotopic spin vector $\frac{1}{2}\ \boldsymbol{\tau}$ and the isotopic orbital angular momentum $\mathbf{K}$ one may form the scalar product $\boldsymbol{\tau} \cdot \mathbf{K}$ invariant under rotations in ω-space. One can then incorporate the isotopic spin in the equation for a free nucleon by writing $(\gamma^i\partial/\partial x_i + M - \boldsymbol{\tau} \cdot \mathbf{K}/\Lambda)\psi(x, \omega) = 0$, where $1/\Lambda$ and the mass M have the dimension of the inverse of a length in a system of units in which $\hbar = c = 1$. The density and current four-vector of the number of heavy particles is then defined as $J^i = \oint\oint\ d\omega\bar{\psi}\gamma^i\psi$, and their charge current and density four-vector as $S^i{}_{\mathrm{h.f.}} = \oint\oint\ d\omega\bar{\psi}\gamma^i\,(I_3+\frac{1}{2})\,\psi$, where h.f. means heavy fermions and where $\mathbf{I} = \mathbf{K} + \frac{1}{2}\boldsymbol{\tau}$ is the total angular momentum in ω-space. Interaction with the Maxwell field is introduced by changing $\partial/\partial x_i$ into $\partial/\partial x_i - ie(I_3 + \frac{1}{2})A_i$. The conservation laws $\partial J^i/\partial x_i = 0$ and $\partial S_{\mathrm{h.f.}}{}^i/\partial x_i = 0$ then follow automatically.

Coupling to the pseudoscalar pion field ϕ (with 3 isotopic components) is introduced by a term $ig\bar{\psi}(x, \omega)\ \boldsymbol{\tau} \cdot \boldsymbol{\phi}\ (x, \omega)\gamma_5\psi(x, \omega)$ in the Lagrangian. With this interaction, J^i is still conserved, but for conservation of S^i one has to add to $S_{\mathrm{h.f.}}{}^i$ the pion charge current and density $S_\pi{}^i$.

One may now consider $|\,\mathbf{M} + \boldsymbol{\tau} \cdot \mathbf{K}/\Lambda\,|$ as the mass operator for heavy fermions. The eigenvalues for this mass follow from a simple eigenvalue problem in ω-space and obviously can be labeled by the quantum numbers of ω-angular momentum. Let $\mathbf{K}^2 = k(k+1)$, $\mathbf{I}^2 = i(i+1)$, then obviously $i = k \pm \frac{1}{2}$ since the ω-spin is $\frac{1}{2}$. Then $\boldsymbol{\tau} \cdot \mathbf{K} = \mathbf{I}^2 - \mathbf{K}^2 - \frac{1}{4}\boldsymbol{\tau}^2 = (k \pm \frac{1}{2})(k \pm \frac{1}{2} + 1) - k(k+1) - \frac{3}{4} = \pm k \pm \frac{1}{2} - \frac{1}{2}$, and for $i = k + \frac{1}{2}$ (with $\mathbf{K}$ and $\frac{1}{2}\boldsymbol{\tau}$ lined up) one finds mass levels $|\,M + k/\Lambda\,|$ with $k = 0,1,2,3, \cdots$, while for $i = k - \frac{1}{2}$ ($\mathbf{K}$ and $\frac{1}{2}\boldsymbol{\tau}$ oppositely directed) one finds mass levels $|\,M - (k+1)/\Lambda\,|$ with $k = 1,2,3, \cdots$. Using spectroscopic nomenclature we find an even $^2S_{\frac{1}{2}}$ ground state M and an odd $^2P_{\frac{1}{2}}$-state $|\,M - 2/\Lambda\,|$. If we identify these states with the nucleon state and the V_1 state (of mass 1.2M) respectively, we find $\Lambda \sim 0.9(\hbar/Mc)$. Because of the different ω-parity of these two states, the V_1 state cannot go over into the nucleon ground state under emission of only photons. The higher-energy levels $^2P_{\frac{3}{2}}$, $^2D_{\frac{3}{2}}$, $^2D_{\frac{5}{2}}$, etc., however, will not be stable but will go over into the nucleon state if they are ω-even, and into the V_1 state if they are ω-odd. In principle, these other levels could be observed as resonances. They lie, however, above the maximum energy obtainable at Brookhaven Laboratory. The existence or nonexistence of these resonance levels will decide the correctness or invalidity of the present theory.

In counting the number of heavy fermions, one should count antiparticles (such as a negative proton) as minus one particle. Thus nucleon pair production does not alter this number.

For creation of a V_1-particle from nucleons, one has to change ω-parity and therefore needs a meson in an ω-odd state $\phi(x.\omega)$. The π-meson corresponds to the $^3S_1$ meson-state in ω-space ($k = 0$, $i = 1$). For these mesons obviously $\mathbf{I} = \mathbf{K} + \mathbf{T}$, where the isotopic spin $\mathbf{T}$ has value 1. The lowest meson states of odd ω-parity are the ^3P_I states with $I = 0,1,2$. The meson mass operator may depend on $\mathbf{K} \cdot \mathbf{T}$ and on $\mathbf{K}^2$. The P_1 state may perhaps be interpreted as the τ-meson. We have an opportunity of understanding the existence and some of the properties of stability or instability of many kinds of particles.

It is now also clear that calculations beyond the g^2-approximation based on the old meson theories cannot lead to correct conclusions, as they do not take into account the higher levels in ω-space.

As for light particles: one may perhaps be able to incorporate them as another family, of "light fermions," among which the electron and neutrino form the ground level, and the muon the first excited level of ω-parity different from that of the electron and neutrino. The differences in property between light fermions and heavy fermions is due not only to the smallness of $e^2/\hbar c$ as compared to $g^2/\hbar c$, but also to the largeness of $(m_\mu - m_e)/m_e$ as compared to the smallness of $(M_{V_1} - M_{\mathrm{nucleon}})/M_{\mathrm{nucleon}}$.

In the animated discussion of Pais' paper, many persons took part.

P. A. M. Dirac (Cambridge) presented a paper on his Lorentz-covariant "ether" theory. A velocity field, which may be orthogonal to a set of space-like surfaces in four-dimensional space, might give a preferred time-direction in each point of space-time. In a quantized theory, there may be a probability distribution for the probability of each direction. The vacuum is an idealized state in which all time directions are equally probable. As this state is not normalizable, it cannot be accurately realized but at most can be approached. The theory has not been worked out in detail, but examples of a theory based on such principles can be given. One such example was discussed by Dirac in some detail. He remarked that space-like surfaces are needed when a Hamiltonian is defined; so, then, why not give them a physical meaning? He had not yet included the electron spin in his theory; this should be done in the future.

In the example discussed, the potential four-vector had a relativistic length m/e. Pais asked which m was meant? Dirac expressed the belief that the electron is more elementary a particle than any other, and that its mass should be used. Other questions were asked by Fokker and by Wouthuysen.

On Friday afternoon, W. Heisenberg (Göttingen) gave a survey of quantum electrodynamics. Dirac's and Maxwell's equations combined lead to infinities, which in the old "subtraction physics" were simply omitted, but which, as suggested by Kramers and realized by Bethe, Schwinger, and several others, are nowadays omitted as allowable renormalizations. The results thus obtained are in agreement with experiment, as discussed by Lamb and by Bloch. The theory also predicts scattering of light by light and the occurrence of a form factor in Maxwell's inhomogeneous equations. Experiments to verify these predictions have not yet been performed.

However, the values of the non-normalized e and m in the fundamental equations from which one starts are infinite, so that one gets results starting from equations which do not exist. Källen showed that this difficulty cannot be avoided by not using perturbation methods. It is not even certain that the renormalization technique will yield finite results from such infinite starting point. It is not impossible that one will have to introduce interactions of nonelectromagnetic nature for obtaining finite results by nonperturbation procedures. Some such more general theory might perhaps also yield a value of $e^2/\hbar c$. With Casimir's theory of the $e^2/\hbar c$ ratio it would be hard to understand why the size of the electron should be 10^{-13} cm.

A closed theory of quantum electrodynamics, without taking into account fields of other particles, can never lead to a complete theory as there are some observable interactions between electrons and mesons. Perhaps it can be hoped that in a complete theory taking into account other interactions, renormalizations will change e and m by small amounts only, and that the $e^2/\hbar c$ ratio will be determined when the mass ratios can be determined in connection with a theory of heavy particles. Perhaps some kind of nonlocality is to be introduced into the theory, either a finite size of elementary particles, or some sacrifice of the principle that signals faster than light are impossible. The question of nonlocality, however, is an experimental question on which information could be obtained by a study of high-energy collisions. Perhaps it is more likely that the interactions are local but are strong. Pais has shown again the importance of finding selection rules and symmetry properties from experiments. As for theories, it may be that one has looked for too complicated schemes.

During the conference, a Lorentz and Kamerlingh Onnes exhibition was arranged in the museum for the history of natural sciences in Leiden.

On Wednesday afternoon the Kamerlingh Onnes Laboratory was visited, in particular the new additions to the cryogenic laboratory, and the small powerful magnet in the basement, which is supposed to be capable of yielding a 100,000-gauss field in the near future. Afterward, there was a memorial session in the main building of the University. Dr. J. Clay gave a short biography of H. Kamerlingh Onnes and of H. A. Lorentz. Dr. W. de Haas described how Kamerlingh Onnes built his laboratory out of practically nothing. Dr. Thysse talked about Lorentz' important work in connection with the Zuiderzee project. It is not sufficiently known abroad that the Dutch have made a science out of the calculation of changes in water levels of rivers and tides to be expected consequent to building of dikes or changing the course of water. A student in this science must, for instance, be able to calculate as an examination problem the tides in the Panama Canal. The correctness of Lorentz' calculations prevented a disaster in the northern half of the Netherlands, when in February of this year the old dikes of the southern part of the country gave way for the storm.

On Friday afternoon, the conference in Leiden was concluded by an open meeting in the lecture room of the Kamerlingh Onnes Laboratory, attended by members of the Netherlands Physical Society. In this meeting, F. London and W. Heisenberg gave the surveys of the proceedings of the conference reported on above.

On Saturday afternoon, in Amsterdam, the members of the conference attended a ceremonial session of the Royal Netherlands Academy of Sciences addressed by R. Kronig (Delft), during which the Lorentz medal was presented to Fritz London. Previous recipients of this medal have been Planck, Pauli, Debye, Sommerfeld, and Kramers. A dinner, Saturday night June 27, in honor of F. London in the Hotel Victoria, Amsterdam, concluded this international meeting of physicists.