THE QUANTUM HYPER-FREQUENCY AMPLIFIER—THE MASER

MICROWAVE electronics is full of novel features and is a fascinating field which in the last decade has made great headway.

The techniques for generation, amplification and transmission at microwave frequencies have had to depart from the methods of radio frequency electronics, in order to overcome certain functional limitations of tubes and transmission lines, commonly employed at lower frequencies. When one is considering propagation in a waveguide, the ordinary two wire line transmission ideas and the concept of current and voltage can no more be visualised in them. The behaviour can only be understood in terms of electromagnetic wave equations.

Similarly, tubes generating microwaves function on a new principle known as velocity modulation in which the electron beam interacts with a tunable cavity or cavities, experiencing in their passage through the tube column, a velocity change, depending upon the sign and magnitude of the exciting alternating voltage. The result is usually a bunching up of electrons with respect to time, and such bunched electrons when they interact with the cavity, transfer energy to it in the form of electromagnetic radiation. The travelling wave tube which is used as an amplifier in the microwave region makes use of a distributed interaction between an electron beam and a travelling wave.

While all the electrical amplifiers in use today, including the above, employ the motion of charged particles in electric or magnetic fields, very recently a totally different method has been discovered for amplifying electrical signals at microwave frequencies. The amplification is achieved by stimulated emission of radiation under suitable circumstances. The device which uses this principle is called a *maser*, the word having been coined from the words *microwave amplification* by *stimulated emission* of *radiation*.

The maser principle was suggested by Weber in 1953 and again independently by Barrow and Prokhorov in 1954. The idea was used in a microwave spectrometer by Gordon, Zeiger and Townes in 1954. In the last few years a large number of papers have been published on the subject analysing the theory and proposing new ways of incorporating the idea into practical devices.

The Principle of Maser Operation

Energy transitions associated with atoms and molecules are restricted to only a set of "stationary states", each of which is characterised by a definite amount of internal energy. In free atoms and molecules, and also sometimes in atoms in a solid, the energy levels are sharp and transitions between them can be induced by electromagnetic radiation of appropriate frequency. If two levels between which transitions take place have energies W_A and W_B, the frequency given to the radiation field or taken from it is given by $\nu_{AB} = W_B - W_A/h$ where h is the Planck's constant.

From quantum mechanical grounds we have, that such transitions are likely, only when the frequency of the radiation that is interacting with the system is nearly equal to ν_{AB}. When the electromagnetic radiation induces a transition in which the atom gains energy, this energy is taken from the electromagnetic wave. Likewise, when the radiation induces a transition in which the atom loses energy, this is added to the electromagnetic wave. This addition is in the form of one photon of frequency ν_{AB} that is coherent with the exciting wave (has the same phase, direction and polarization).

A very general thermodynamic argument due to Einstein proves that the probability, that the radiation will induce an atom that is in state A to go into state B is equal to the probability that the same radiation will induce the reverse transition, that is from state B to state A. When matter is in thermal equilibrium the number of species in the ith state is proportional to $e^{-w_i/kT}$, where w_i is the energy of the ith state, k is the Boltzmann constant and T is the absolute temperature. If the state B has higher energy than state A, the ratio of the number of species in the two states will be

$$\frac{N_B}{N_A} = e^{-h\nu_{AB}/kT} .$$

If the atoms are in thermal equilibrium at any temperature T, there are more atoms in the lower state than in the higher state and therefore, more transitions upwards take place than in the reverse direction. This would result in a net absorption of energy from the radiation. If, however, by some means we can get more atoms or molecules in the higher energy state than in the lower, there will be a net transfer of energy to the radiation field which would result in power being added to the electromagnetic wave. This would result in amplification, and is the principle of operation of the maser amplifier.

Thus, for a maser to function as an amplifier at a given frequency, a working substance, namely, an atom or molecule, with energy levels having the requisite separation and between which the probability of induced transition is sufficiently large should be chosen. A suitable method should also be found to collect more atoms in the upper state than the lower. Finally, it is necessary to devise a technique for the radiation to interact with the working substance. A number of ingenious masers have been built and operated but all of them in the microwave region.

Maser Employing Ammonia Molecule

The configuration of the ammonia molecule is a triangular pyramid with the nitrogen at the top of the pyramid. Two configurations are shown in Fig. 1 and these have different energies, one representing the ground level and the other lying at an energy level slightly above. Transition between these levels can take place and this is known as 'Ammonia inversion' discovered by Cleeton and Williams in 1937. The frequency of this transmission is in the microwave region at 24,000 Mcs. per second ($\lambda = 1 \cdot 25$ cm.).

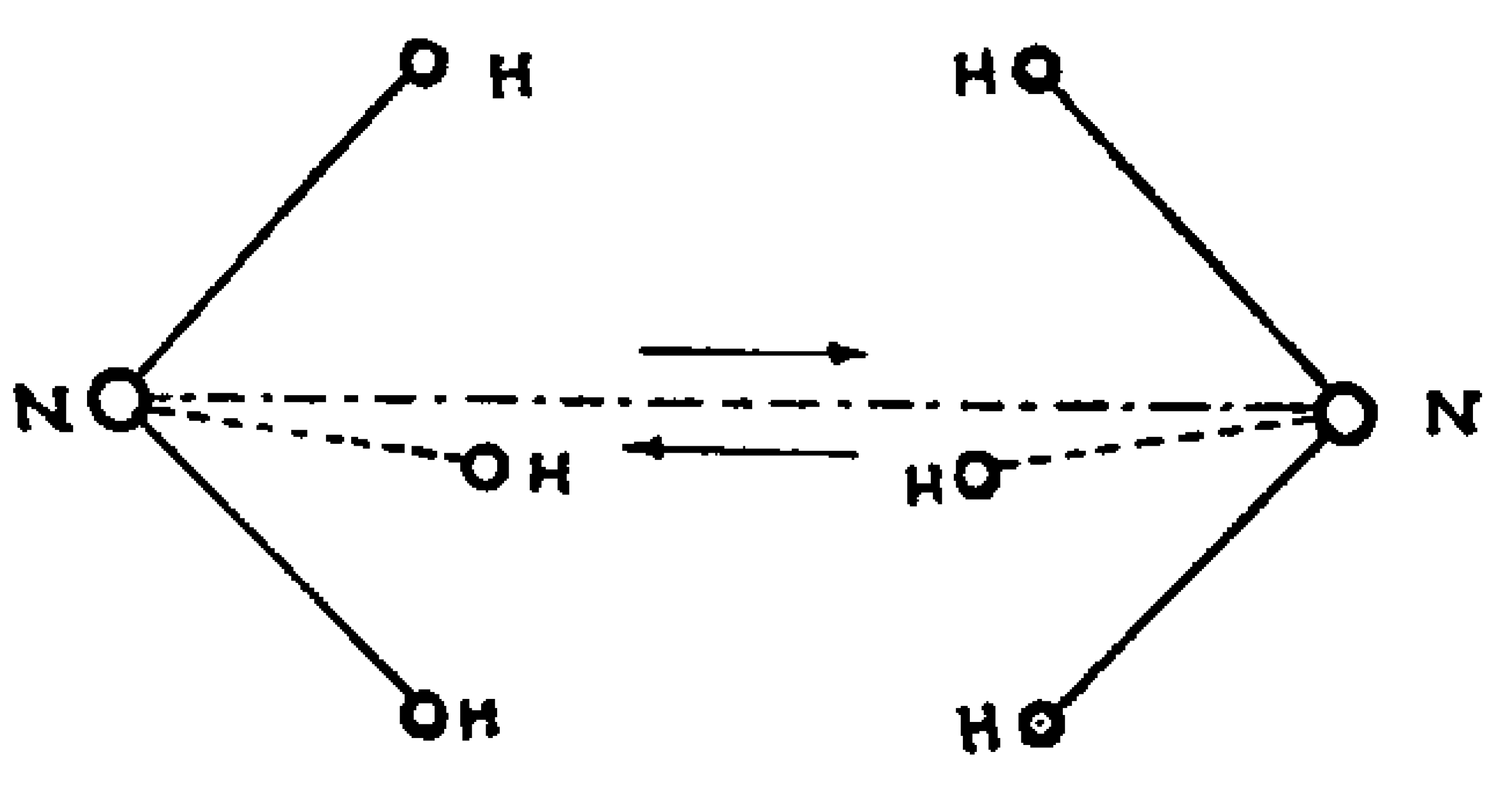

FIG. 1. Ammonia Inversion.

In employing ammonia for maser operation, the segregation of the species lying at the higher energy level is achieved by making use of the Stark effect. The ammonia molecules, as a well-collimated beam issue forth from a source chamber S [Fig. 2 (a)] and the beam is directed along the axis of an electro-static focussing system consisting of four or more electrical conductors [Fig. 2(b)] that are made alternately positive and negative.

In such a focussing system of electrodes the gradient of the electric field strength is away from the centre of the beam. Molecules in the upper state are pulled in, towards the beam axis, while those in the lower state are expelled outward from the beam and thus physical separation of the molecules in the two states is accomplished. Molecules in the upper energy level is allowed into a microwave cavity C [Fig. 2 (a)] resonant at 24,000 Mcs.

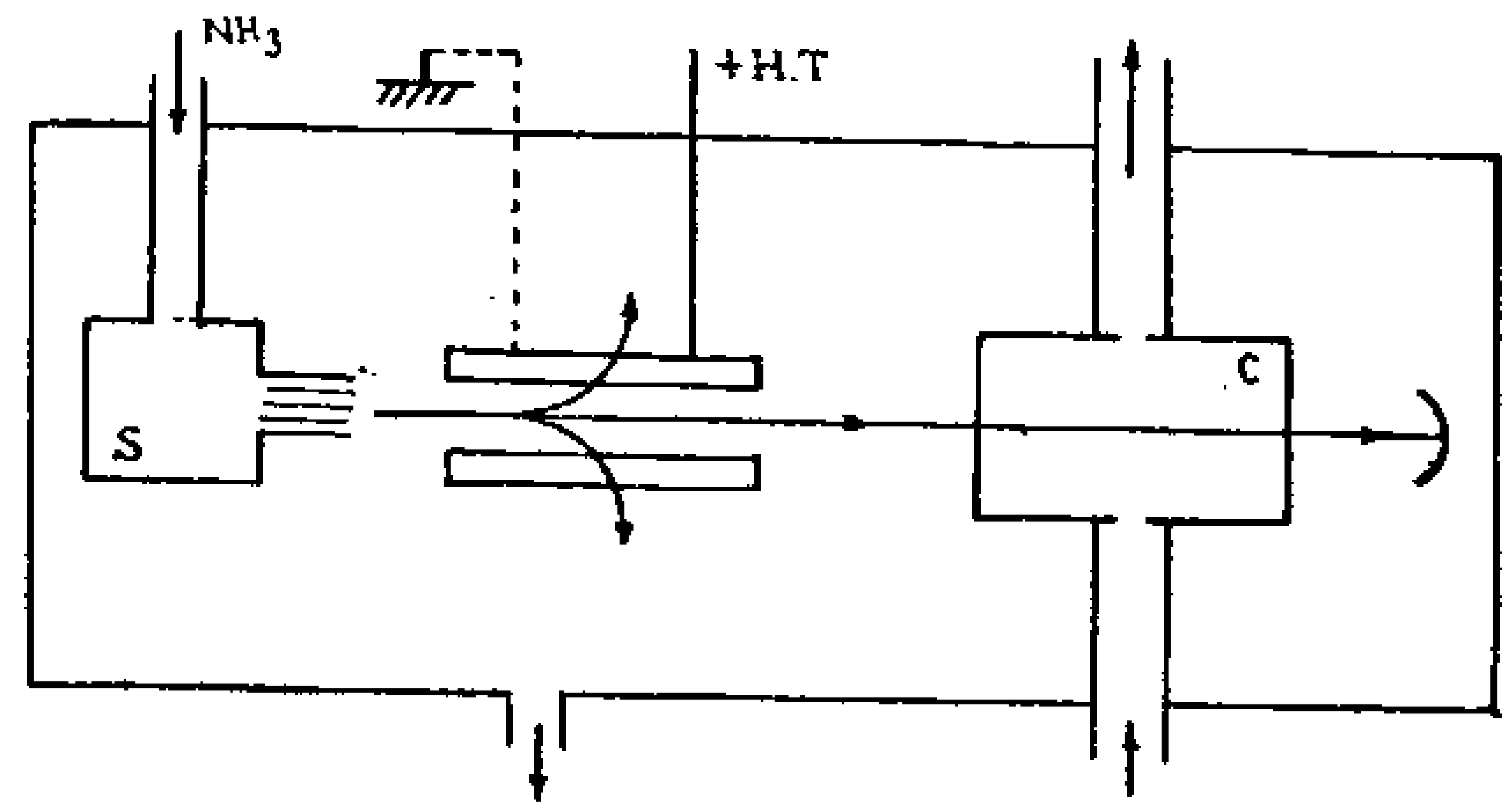

FIG. 2 (a)

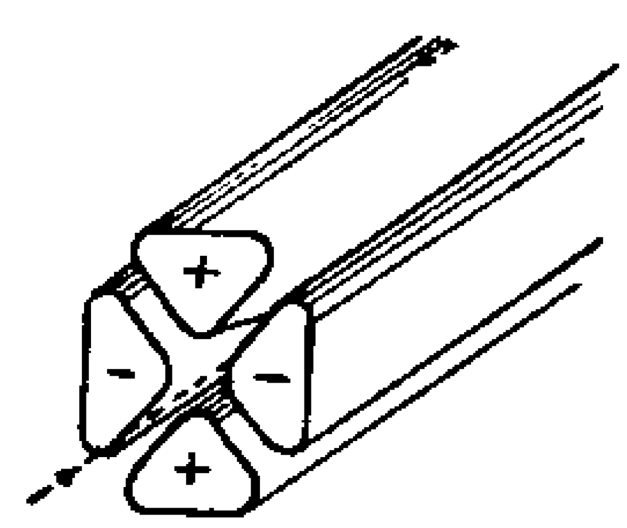

FIG. 2 (b)

FIG. 2 (a). Diagrammatic Representation of a Molecular Amplifier.

FIG. 2 (b). Focussing Electrodes.

If, now, microwave wave radiation of this frequency is fed into the cavity, the molecules in the higher state give up their energy by stimulated emission of the same frequency and add radiant energy to the cavity. The radiation can induce the reverse transition and take up energy from the cavity. This, however, does not take place to any appreciable extent since a continuous stream of fresh charge of molecules at the higher energy level is brought into the cavity, and spent molecules are pushed out. Thus, on the average, energy from the molecule is added to it. If this gain in energy is greater than the losses in the cavity, more power can be taken from it than is supplied. Amplification at the frequency of 24,000 Mcs. has been obtained with ammonia molecule as the working substance.

An amplifier of this type can also be used as an oscillator. Such oscillators have very high frequency stability. The frequency of such an oscillation has been observed to have a random drift of only one part in 10^{13} in a period of two hours. The power output of the ammonia maser amplifier is low—of the order of 10^{-10} watt. But the great advantage of the ammonia maser is the low internal noise compared to the conventional amplifiers and because of this, amplification of very much weaker signals is possible with masers.

Solid State Maser

The most successful maser amplifiers developed so far have been solid state three-level masers. Energy levels in a solid are very broad generally, but there are some atoms belonging to the transition and rare-earth elements notably, possessing sharp enough energy levels to be used as masers. Since such atoms are situated in a crystal lattice the levels undergo splitting because of Stark effect due to internal crystalline fields. Application of a magnetic field causes further splitting of the Zeeman type.

In Fig. 3 are represented three energy levels in a crystal. When the levels are in thermal

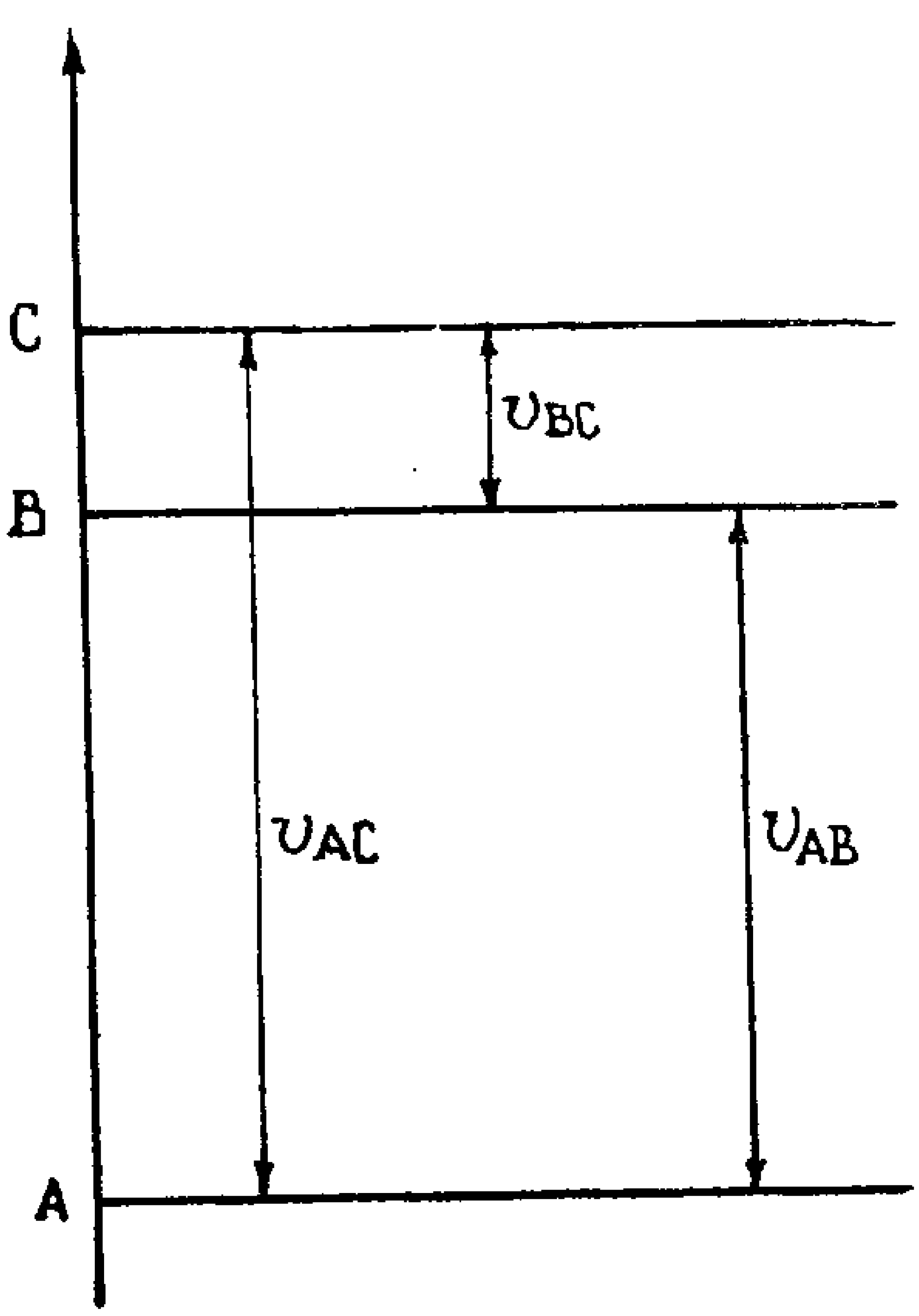

FIG. 3. Energy Levels in a Solid State Amplifier.

equilibrium the relative population in levels B and C will be $e^{-h\nu_{AB}/kT}$ and $e^{-h\nu_{AC}/kT}$ times the number in level A. When the crystal is exposed to intense radiation of frequency ν_{AC} a new equilibrium will be established, which equalises the numbers in levels A and C. The number in B however will be either less or greater than A or C, depending upon the relative transition probabilities. If the transition probability for transition C-B is greater than B-A the number in B will be in excess of A. On the other hand, if the transition probability B-A is greater than C-B the number in level B will be less than in the levels A or C. In the former case where $T_{CB} \gg T_{BA}$ a maser operation of the crystal is possible at the frequency ν_{AB} while on the other hand when $T_{BA} \gg T_{CB}$ maser operation is possible at frequency ν_{BC}.

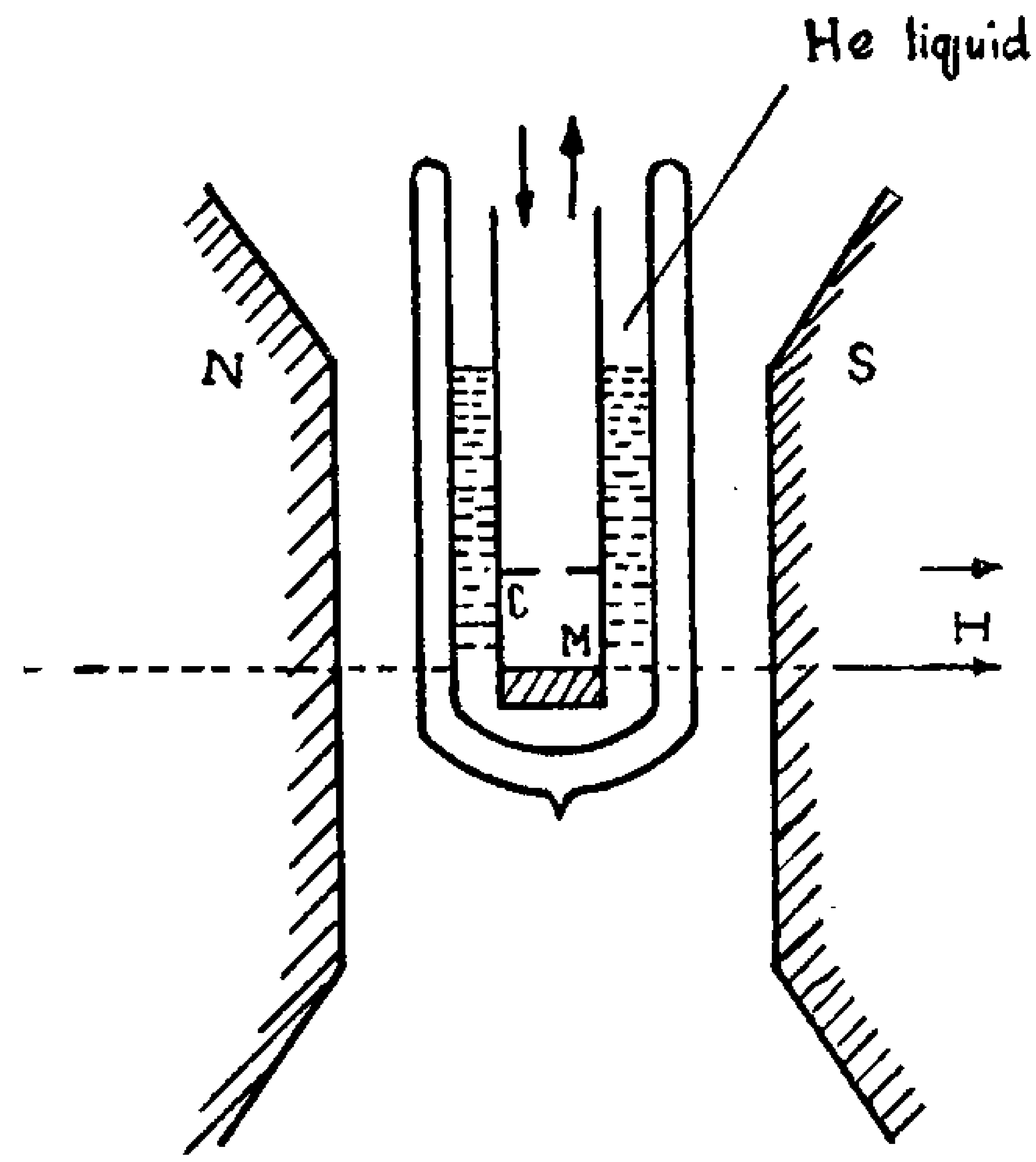

FIG. 4. Solid State Amplifier Operating at Liqd Helium Temperature.

Solid state masers are operated at liquid helium temperatures (4° K. or lower) for several reasons. The maximum gain obtainable will depend upon the population difference between levels B and A (N_B/N_A large). The maximum value of this ratio is $e^{-h\nu_{BC}/kT}$. If therefore the population in B has to be greater ν_{BC}/T should be large. Hence, the lower the temperature is, the higher the gain. Another important reason for operating at low temperature is that the desired low values of the lattice induced transition probabilities are attainable only at low temperatures. An enhancement of this transition probability contributes to the noise level of the amplifier. Further, such enhancement necessitates the expenditure of more power to maintain the equilibrium of population densities.

In spite of difficulties, successful amplifiers of this type have been constructed at Bell Telephone

Laboratories by Scovil, Feher and Seidel and by J. W. Meyers at the Lincoln Laboratory, M.I.T. The Bell Telephone maser uses a gadolinium atom in a crystal of gadolium ethyl sulphate, operating at 9,000 Mcs. The Lincoln Laboratory maser uses chromium atoms in potassium chrom cyanide and operates at 2,800 Mcs. It amplifies linearly upto an output of 10^{-6} watt with a maximum output of 10^{-5} watt. The amplifier has gains of 40 db. and 10 db. with bandwidths of 25 and 500 Kcs. The noise temperature has been estimated conservatively at 100° K.

Negative Temperature Maser

In this method the atoms are placed in a magnetic field H, where the ground state splits into a number of magnetic sublevels. The energy of the ith sublevel, with respect to its zero field value, is given by

$$E_i = \mu_0 g M J_i H$$

where μ_0 is the Bohr Magneton, g is the Lande 'g' factor and MJ_i is the component of the total angular momentum of an atom in the ith state in the direction of the magnetic field, in units of $h/2\pi$. When thermal equilibrium is established, the number in each level is proportional to $e^{-E_i/kT}$. Now, if the direction of the magnetic field is suddenly reversed, the value of MJ_i for each state is suddenly multiplied by -1. A state that had energy E_i, now has energy $-E_i$. Thus, the population of these states become proportional to $e^{+E_i/kT}$, the distribution they would have according to the Boltzmann formula for a temperature of $-T$; hence the term negative temperature. We have thus the requisite condition for maser operation, namely, a greater number of atoms in the upper state than in the lower.

Though this maser has got the advantage that it can be tuned to different frequencies by varying the magnetic field, it has other disadvantages. The operation of the maser will be intermittent because the energy source has to be periodically recharged. Further, a very low noise temperature is required in order to obtain a large population difference between the states.

Optically Pumped Maser

Though a maser of this type has not been successfully operated so far, the idea of obtaining an excess population by optical pumping process is an interesting one. The case can be well discussed by taking sodium atom.

The familiar yellow lines in the spectrum of sodium atom are produced by transition from $^2P_{3/2}$ and $^2P_{1/2}$ states, to the ground $^2S_{1/2}$ state (see Fig. 5). When a sodium atom is placed in a magnetic field these levels undergo Zeeman splitting. The frequency that causes a transition between the $MJ = 1/2$ and $MJ = -1/2$ sublevels into

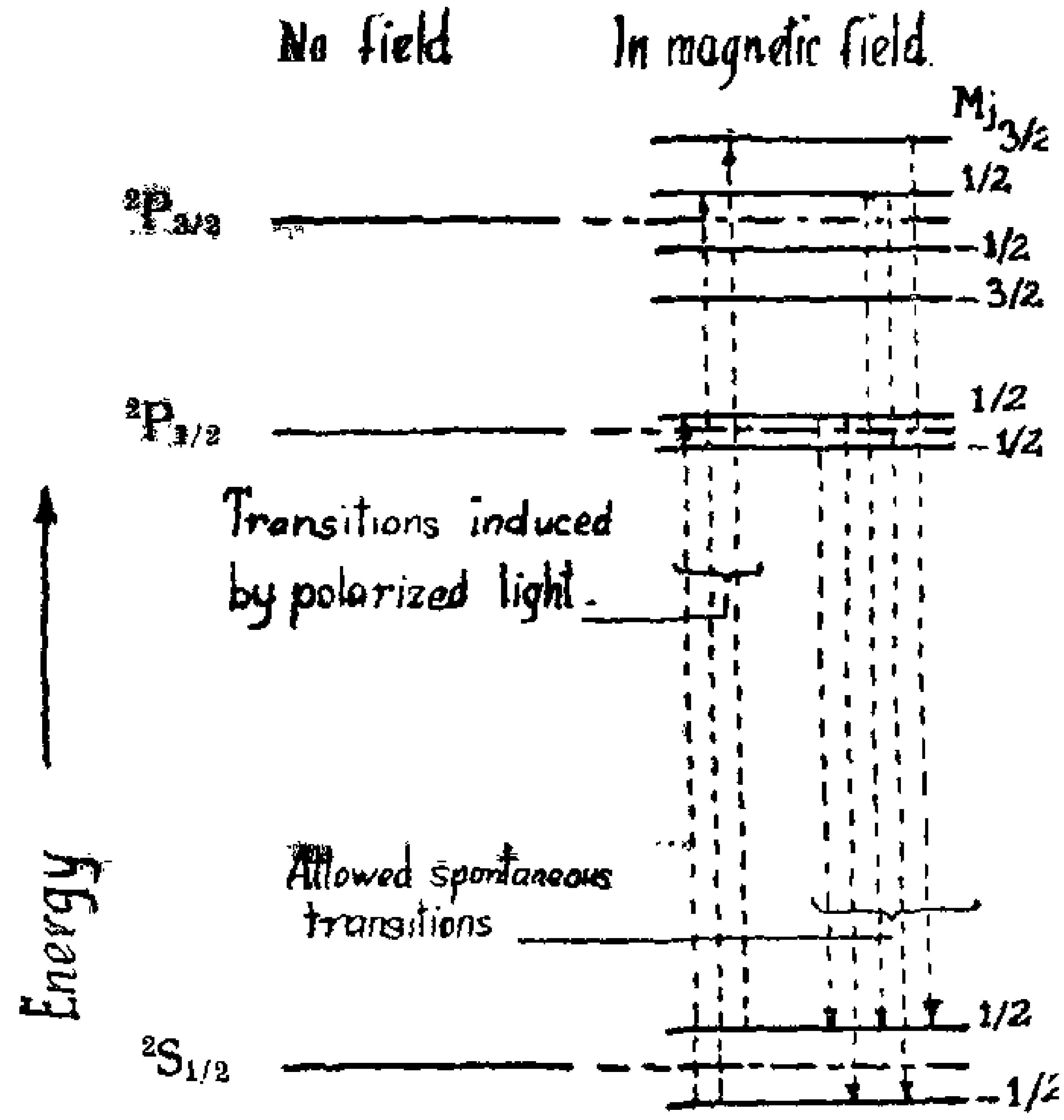

FIG. 5. Energy Levels in Sodium Responsible for the Yellow Lines and their Splittings in a Magnetic Field.

which the ground state splits is 5·6 megacycles per gauss of the applied. If circularly polarised light from a sodium lamp is directed into the sodium vapour kept in the field along the direction of the applied field, the light is absorbed by atoms in the ground level, undergoing excitation into one or the other of the ^2P levels. Because of the circular polarisation of the light, only transitions in which MJ changes by 1 are allowed. These excited atoms spontaneously emit a photon and drop down to one of the ^2S levels, the allowed transition in this case being for changes in values of $MJ = \pm 1$ or 0. It can be seen from the diagram the atoms can be pumped into the higher of the ^2S states resulting in an excess population at the level.

This principle as stated at the outset has not resulted in any practical form of maser but offers promising possibilities.

Though the maser technique is of very recent origin and has not yet passed out of the research stage to the concrete instrumental stage, its possible future applications has aroused much interest. As stated, the low noise characteristic of this amplifier makes it especially suitable for greater ultimate sensitivities in the field of radio astronomy, communication and radar. Especially, in radio astronomy where the signal strength is much smaller than the noise of the presently available amplifiers, this new principle of amplification would have very fruitful applications. Masers can be designed to oscillate at very stable frequencies, thus providing highly accurate time standards.

A. JAYARAMAN.

MAX PLANCK

THERE are events in the development of Physics which reach far beyond the boundaries of science and have a decisive influence on the fate of humanity as a whole. Max Planck's *Quantum Theory* is an example of such a revolution of thought. Twenty-third April 1958 marks the 100th Anniversary of the birth of one of the greatest theoretical physicists of our times. Max Planck was born in Kiel on April 23, 1858, of family which had produced many government officials, jurists and scientists. When he was nine years old, his family moved to Munich. There, he attended the Maximillan Gymnasium and studied at the University for three years, acquiring a solid knowledge of Physics. However, the real spirit of research in Physics became apparent to him, only when he first came into touch with the work of Helmholtz, Kirchhoff and Clausius in Berlin.

Until 1877, Max Planck was a University Instructor in Munich. Two years later the Philosophy Faculty of the University of Berlin offered him a chair. Thus, Planck came in a world centre of science to work at the side of his venerated and admired Helmholtz. Here he advanced his thermodynamic research and arrived, thereby, at an entirely new field—Thermal Radiation.

From 1896 onwards Planck's principal goal was the theoretical derivation of the Laws of Radiation. Entropy had always appeared to him to be the essential concept of the Thermal Theory. Planck then turned to radiation and discovered the famous Radiation Formula which he made public at a Meeting of the Berlin Physics Society on October 19, 1900. He recognized that radiated energy was not arbitrarily divisible, but had a type of atomic structure, or, as Planck said, exists in an ascertainable fixed quantum. The radiated energy quantum of a fixed frequency is proportionate; the proportionality factor signified by letter 'h' is a universal constant, which Planck called the efficiency quantum—usually called simply "Planck's Constant".

In 1905, Einstein took up the quantum idea. He showed that Planck's first interpolative derivation of the Radiation Formula can be so expanded that the existence of the energy quantum appears to be an inevitable result of the observed spectrum of thermal radiation. He further showed that there are many other phenomena of an entirely different sort where the quantum comes under observation directly, as light quanta—or, as it is called today, a Photon—for instance in photo-electric effect.

At the insistence of Planck, Einstein was called to Berlin in 1913 to a special position in the Prussian Academy where he could pursue his research without the burden of teaching duties.

Through the united efforts of Planck and Einstein, Berlin was the world centre of theoretical physics for almost twenty years. Two of the most eminent of them, Max von Laue and Lise Meitner, also worked in Berlin in this period and contributed to the lustre of physics in that Capital. Students who wished to hear Planck's famous lectures streamed in, from every land. These lectures were printed in six small volumes and contributed much to the dissemination of Planck's ideas. Planck was made permanent Secretary of the Mathematics and Physics Department of the Berlin Academy and gave much time and effort to this task. In 1928 at the age of seventy he retired from his teaching position at the University of Berlin. His successor was Erwin Schrödinger, one of the discoverers of wave mechanics. However, Planck retained the leading position at the Academy.

When the National Socialists seized power in 1933 and began to dismiss many officials and professors because of political unacceptability or Jewish ancestry, Planck, as President of the Kaiser Wilhelm Society, attempted to intervene with Hitler on behalf of various colleagues. He had no success. Einstein announced his withdrawal from the Academy and thereby spared his friend the humiliation of having to inform him of his expulsion. Schrödinger, although uncontested, resigned his Professorship of his own free will and went abroad. The great period of theoretical physics was over in Berlin.