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## THE REGION OF EXTREMELY LOW TEMPERATURE.\*

NOW that the war is over, we may turn back and follow, as we used to do, one of the attractive paths of science and examine what has been accomplished in investigation of low temperature phenomena. That there has been a great stimulation of certain lines of scientific effort due to the war is well known to all, and in most laboratories war problems have displaced all others. The scientific men of Canada, however, have been called upon but very little to give their time and peculiar powers to the solution of the problems of warfare. Notwithstanding this, even in Canada, productive investigation has diminished. Almost nowhere has the work of investigation in pure science not been interrupted. In the Universities of Holland, however, the continuity has not been broken, and while even in these institutions, laboratory assistants were drafted in 1915-16, owing to the fact that the Universities are state controlled, it was not difficult to secure leave of absence for men deemed indispensable to the work of the laboratories. The people of Holland are proud of their universities and are generous with them, and a productive scholar is given every encouragement.

At Leiden is one of the most famous laboratories of the world, both because of its peculiar history and the line of its activity. The universities of that little country are so closely related that one may think of them almost as a single institution. By a sort of understanding, the physics laboratory of each pursues its own definite line of research. For example, at Amsterdam, Zeemann and his colleagues are interested in problems in radiation and work on them almost exclusively, while at Leiden, Kamerlingh Onnes and his staff are engaged in the study of the fundamental properties of matter, and in particular of certain substances, the so-called permanent gases.

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Ever since the time of van der Waals in 1870, the energies and facilities of this laboratory have been turned toward the study of gases and their liquefaction and solidification, because, in this way, much can be learned of the structure and properties of matter.

We may understand the general problem of such investigations by consideration of such a typical substance as water. If we lower the temperature of water to  $0^{\circ}\text{C}$ . it freezes or becomes ice. Again, if we raise the temperature of water in an open vessel to  $100^{\circ}\text{C}$ . the water passes into steam or vapour. Both ice and steam are water, chemically speaking, but their physical properties are very different from those of ordinary liquid water. We find similar phenomena with other substances. Lead is solid at ordinary temperatures, but if the temperature be raised to  $327^{\circ}\text{C}$ ., the lead melts and becomes liquid; if we heat it to about  $1500^{\circ}$ ., it boils and becomes vapour. Even iron may be melted and vapourized. The temperature of the sun is so high that its atmosphere contains iron in the form of vapour. On the other hand, if we take air, which, at ordinary temperature is a gas, and cool it sufficiently, it becomes a liquid and if cooled still more it becomes a solid, resembling ice. In general, then, the condition in which we find any substance depends on the temperature. If we raise the temperature sufficiently, all substances may be vapourized, and, we believe, if we lower it sufficiently, that all substances may be solidified. Only one substance, helium, has resisted all efforts to liquefy it. Here is one of the unities of Nature, a great law of corresponding states.

Obviously, two lines of attack are open to investigate these states of matter and the transitions from one to another. We may raise the temperature and liquefy solids and vapourize liquids, or, we may lower the temperature and liquefy gases and solidify liquids. There are several good reasons why the latter method has been chosen at Leiden. To begin with, manipulation of bodies at high temperature is attended by great experimental difficulties. Apparatus becomes very difficult to build and handle and the control of the temperature becomes very difficult. Again, there is a better chance of discovering fundamental truths at low temperatures than at high,

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partly because we may approach nearer to the lowest level of temperature than we may the highest known temperature and partly because there is an actual lower limit, while, so far as we know, there is no upper limit.

Everyone is familiar with the construction and use of thermometers. The commonest is made of mercury enclosed in glass. This may be used from  $-39^{\circ}\text{C}.$  to perhaps as high as  $500^{\circ}\text{C}.$ , when properly made. At  $-39^{\circ}\text{C}.$  mercury freezes, while it boils at  $357^{\circ}\text{C}.$  Alcohol, toluol, and some other liquids, which have lower freezing points, can be used for temperatures below  $-39^{\circ}$ . For higher temperatures than can be measured with the mercury thermometer we may resort to gas and electrical thermometers. Also, for very low temperatures we use gas and electrical thermometers again.

Let us suppose that we had a thermometer made of some hypothetical substance so that it could measure all temperatures from the lowest to the highest known. The freezing point of water is at  $0^{\circ}\text{C}.$  and the boiling point at  $100^{\circ}\text{C}.$  Compared with the entire range of this hypothetical thermometer, the distance between the points beyond which life is impossible, seems almost infinitesimal, and we are tempted to ask whether our presence on the earth and the possible living conditions which we find here, are not merely an accident of temperature, or a transitional phase in the great sweep from sun temperatures, or higher, down to absolute zero. We are very dependent on the temperature of our surroundings. A permanent change of  $50^{\circ}$  in either direction would change this planet to such an extent that it would hardly be recognizable except from its dimensions. According to Humphries, the effect of one severe volcanic eruption per year would be sufficient to bring on an ice age. Even two or three near together might lower the temperature of the surface of the earth sufficiently to decrease the production of food to the point of famine. The volcanic dust, which is thrown into the air in such an eruption, is so fine and is thrown so high that it floats for a long time in the quiet upper strata of the atmosphere and becomes almost uniformly distributed over the globe. Thus, it acts as a great curtain and cuts down the amount of heat received at the surface of the earth.

Down at the bottom of our thermometer is the lowest possible temperature,  $-273^{\circ}\text{C.}$ , and at the other end is the hottest temperature known. On this thermometer the sun's temperature is about  $7000^{\circ}$ . There may be places hotter than this, but there is no temperature lower than the lowest, i.e., lower than absolute zero. Many people have some difficulty in understanding how there is a lowest, but not a highest temperature. The reason lies in the nature of matter, heat and temperature.

If we could imagine ourselves gifted beyond all existing men and could be endowed with extreme ultra-microscopic powers of sight, quickness of vision and brain operation together with extreme lightness of touch, we might take a crystal like salt, for example, and divide it continually into smaller and smaller pieces. We could do this over and over again, obtaining smaller fragments of salt at every step, until we came to a point where further division would yield not salt, but its components sodium and chlorine. These particles of sodium and chlorine are the units out of which the salt crystal is built, the bricks forming the structure. They are called atoms and are the ultimate particles of matter considered in the ordinary sense. They are arranged in a definite cubical order and are regularly spaced. Each sodium atom is attached to six chlorine atoms and each chlorine atom is attached to six sodium atoms. This startling simplicity and regularity of structure has been demonstrated by a most interesting and ingenious application of the X-ray bulb. Similarly, other crystals are built up in a regular way with atoms as units but not with this extreme simplicity.

When a liquid or a solid evaporates the atoms leave in pairs or groups and form a vapour and we can then determine the size of the particles and show that each consists of a pair, or a group of atoms. We call this group a molecule. Similarly, all gases are found to have a molecular structure. The molecules of gases are true molecules in the older sense of the word, while in crystals we cannot pick out definite pairs or groups and speak of them as molecules.

The particles of a substance (the atoms or molecules as the case may be) are in constant motion. In a solid this mo-

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tion is a simple vibratory motion and apparently is complicated by so many crowding and attracting atoms; in a liquid the atoms must have considerable freedom of motion, while in a gas this motion consists mainly of darting about in the vessel in which the gas is found. We think of the temperature of a body as determined by the energy of this atomic vibration. This means that temperature is a measure of this energy. The more rapidly the particles move, the higher the temperature. As the temperature is lowered, the motion becomes less and less rapid until at absolute zero it ceases. On this ground, then, we may believe that there is an absolute zero. We may have a zero of motion but no upper limit. There are other better and more convincing grounds for belief in this lowest temperature but they are beyond the scope of this paper.

Thus we see that reduction of temperature means a change in the motion of the particles, a slowing up of their velocities, and we may expect light on the question of the structure of matter if we study it at low temperatures, which we could hardly hope to gain at high temperatures. Besides, the experimental difficulties are not so great. We can find substances of which to build our apparatus that will resist cold, but will not so easily resist heat. For too much motion of the atoms brings about disintegration with liquefaction or vapourization, while diminution of their motions may produce changes, but these are not serious from the mechanical point of view.

The work of the past decade, largely at Cambridge and Manchester, has shown that we can say something about the internal structure of the atom. For example, we know that the atom is made up of electricity, at least in part, perhaps entirely so. According to the best authorities we have a positive charge acting as a sort of sun and a set of negative charges somewhat like planets whirling around the attracting centre.\*

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\*There is a different view of the atom that is gaining ground, particularly amongst chemists. This postulates a positive nucleus and attendant electrons, but these are stationary and occupy approximately fixed positions. It must be admitted that this view, while introducing new difficulties, avoids many that appear in the theory of revolving electrons.

Just how these are arranged is not yet perfectly certain, but it seems probable that the hydrogen atom consists of a central heavy, very small mass of positive electricity and an associated negative electron which is very much larger in size, but much less massive. The helium atom consists of such a central positive charge and two negative electrons. Then, when we come to heavier and heavier atoms we have more and more of these satellites. The motions of these satellites give us light and kindred radiations. Of course, when the atoms vibrate, the motion of vibration is shared by the electrons, so that the radiation from the atom is affected by the temperature. In other words, while the motion of the electron in a sense is independent of the motion of the centre of the atom, it is influenced by it. Hence, if we can cool bodies to approximately absolute zero, we may reduce the motion of the electrons to relatively simpler paths. No doubt, gravitation, chemical affinity and other types of force between bodies will turn out to be due to the properties of these electrons. So development of low temperature research holds great promise for the unravelling of some of Nature's secrets. It is not strange then that at Leiden the greater part of the time is spent on the study of materials at low temperature. It requires, however, expensive equipment and a high degree of technical skill and can be done at only a very limited number of laboratories, which are especially fitted for such work. Sir James Dewar in London, Linde of Berlin, Kamerlingh Onnes at Leiden, Olzewski and Wroblewski in Russia, and Pictet and Cailletet in France have had such laboratories. There are none on this continent.

Before turning our attention to actual accomplishments, we may examine how the temperature is measured when it is so low. The electrical resistance of metals increases as the temperature rises and the amount of this change may be used as a measure of the temperature. [Experiment shown]. Also the pressure of a gas increases with the temperature since the motion of the particles becomes more energetic, as the temperature rises. Hence, this change in pressure may be utilized to measure the temperature. [Experiment shown]. The difficulties increase as the temperature becomes lower,

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because we are not sure of the laws of the changes in these phenomena at extremely low temperature, until they are investigated. So, different methods must be employed and the properties of the substances used as thermometers must be investigated as we go along. For example, air cannot be used in a thermometer below its boiling point,  $-190^{\circ}\text{C}$ . For lower temperatures, hydrogen may be used; for still lower, helium; while for temperatures below the boiling point of helium, its vapour under low pressure may be used. In this way temperatures have been measured down to within less than  $2^{\circ}$  of absolute zero.

We may now turn to the methods for producing low temperatures. There are four general methods.

1. Freezing mixtures. The normal freezing point of water is  $0^{\circ}$ , and, as is well known, ice melts at the same temperature. Whenever ice and water are together, unless the temperature of the water is already zero, the ice will be melted and heat will be abstracted from the water, cooling it. This melting and lowering of temperature will continue until either the ice is all melted or the temperature of the water falls to zero. Ice and water together at  $0^{\circ}$  are in equilibrium. The freezing point of water is lowered by the addition of substances like common salt, for example. In other words, a salt solution will not freeze until the temperature is lowered below zero, the amount of lowering necessary, depending on the concentration of the solution. If ice be placed in such a solution it will melt and the temperature will be lowered. The process will not stop, however, when the temperature falls to zero, but will continue until the temperature falls to the freezing point of the solution. While ice and water are in equilibrium at  $0^{\circ}$ , the salt in the water continues to abstract water from the ice and the temperature is reduced. It is as though the salt in solution were not satisfied with the water already present but demanded more. The table shows the temperatures available with different salts, and the concentrations of the solutions.

|                        |               |        |
|------------------------|---------------|--------|
| Calcium chloride ..... | $-55^{\circ}$ | 29.8 % |
| Sodium chloride .....  | $-22^{\circ}$ | 23.6 % |

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|                         |        |        |
|-------------------------|--------|--------|
| Sodium bromide .....    | -24°   | 41.33% |
| Sodium nitrate .....    | -17.5° | 40.8 % |
| Ammonium chloride ..... | -15°   | 19.27% |

If the temperature falls below the value given for any salt in table, the solution freezes as a mixture of ice and salt crystals. Such a frozen mixture is called a cryohydrate. Ordinarily, when a salt solution freezes, it freezes as pure water leaving the salt in the unfrozen brine. A large bottle of any colored salt solution freezes in an interesting manner. It begins freezing as clear ice in the layers next to the glass and freezes inward as the temperature falls lower and lower. The concentration becomes greater and greater until at the cryohydric point the solution freezes as a colored mass. A glance at the table shows the temperatures necessary to accomplish this for different salts. If ice be placed in a solution of any of these salts the temperature is lowered and may reach the cryohydric temperature. Thus we have a means of producing moderately low temperatures.

2. Boiling under reduced pressure. Water boils at 100° under atmospheric pressure because the pressure of its vapour at this temperature is equal to the atmospheric pressure. Consequently, the tiny bubbles of air contained in the water are filled up with water vapour at atmospheric pressure and any additional pressure, even if very slight, causes these bubbles to grow, filling with vapour as they grow, until they rise to the top of the liquid and burst. Consequently, if we lower the pressure of the air on the liquid it will boil at a lower temperature. The heat abstracted during the boiling is the cause of the lowering of the temperature.

If the pressure be kept constant, the temperature of the boiling liquid may be maintained accurately constant for many hours. With ordinary ether the temperature may be lowered to approximately -100° if the vapour be removed by a powerful pump. Water may be boiled in this way and actually frozen by the abstraction of heat. [Experiment shown].

In the following table are given, in order, normal boiling points of common liquids, freezing points, and critical temperatures. The critical temperature of a substance is the

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temperature above which it is not possible to liquefy its vapour by pressure.

| Substance             | Boiling<br>Point | Freezing<br>Point | Critical<br>Temperature |
|-----------------------|------------------|-------------------|-------------------------|
| Methyl chloride ..... | -23              | -91.5             | 141.5                   |
| Ethylene .....        | -101.5           | -169              | 10.1                    |
| Nitrogen .....        | -195             | -213              | -149                    |
| Oxygen .....          | -181             | -220              | -119                    |
| Air .....             | -190             | -210              | -140.7                  |
| Hydrogen .....        | -252.7           | -257              | -238                    |
| Helium .....          | -268.8           | ?                 | -267.8                  |
| Ammonia .....         | -33.5            | -75.5             | 132.3                   |
| Water .....           | 100              | 0                 | 374                     |
| Mercury .....         | 357              | -39               | 1270                    |

We see that we have a great variety of liquids which we may use for reduction of temperature in this way. Of course the temperature must be lowered to a point below the critical temperature before the gas may be liquefied by pressure. Then, when it is liquefied, if the pressure be lowered, the temperature may be reduced even to the freezing point of the liquid, perhaps a little lower. Liquid helium boiling under reduced pressure reaches the temperature  $-271.85^{\circ}$ , or only a little over a degree above absolute zero.

3. Cooling of gases by Adiabatic Expansion. If a gas be compressed or expanded in a chamber which is impervious to heat, no heat can flow into or out from the gas and the process is called adiabatic. When a gas expands adiabatically it is doing work and is cooled. In the French liquid air machine, invented by Claude, this principle is utilized. The air is first strongly compressed. This compression raises the temperature to a very high point, the compression being practically adiabatic. So the heat produced must be removed by circulating cold water around the pipes through which the air passes. The compressed air is expanded in a small motor and it emerges from the motor reduced in temperature. This cooled air passes back to the compressor through pipes surrounding the pipe bringing the compressed air to the motor so that the new air reaches the motor somewhat reduced in

temperature. This regenerative process goes on with continuous reduction of temperature until the air liquefies as it expands out of the motor. This method of producing liquid air seems to be the most successful of any for large installations.

4. The cooling of gases by the Joule-Kelvin effect.

If a gas be expanded from a high pressure to a lower pressure it suffers a slight change of temperature due to a readjustment of the internal energy. It is found that at ordinary temperature hydrogen and helium are slightly warmed, while all other gases are cooled slightly. The amount of the cooling or heating depends on the temperature at which the gas is taken for the experiment. If the experiment with air is carried out at a lower temperature, the cooling effect is greater. If we perform the experiment with hydrogen below about  $-90^{\circ}$ , we find that the gas is cooled by this expansion just as in the case of air, while if we operate with air at a very high temperature it is heated. This is only another example of the law of corresponding states.

To liquefy air by utilizing the Joule-Kelvin effect, the air is first compressed as in the Claude process and expanded through a small opening, cooling itself as it expands. The same regenerative process is applied as in the Claude process and the temperature is finally lowered to the temperature at which air liquefies, viz.,  $-190^{\circ}$ .

In the early days of low temperature investigation freezing mixtures and boiling under reduced pressure were commonly used. So at Leiden we find a series of operations for production of low temperature. Methyl chloride will liquefy if compressed only a little—a few atmospheres suffices. It is then boiled under reduced pressure with the aid of a powerful vacuum pump, by which means the temperature is lowered to  $-90^{\circ}$ . Then ethylene, which has a critical temperature of  $10^{\circ}$  and thus cannot be liquefied at ordinary temperature, is cooled in the cold of the methyl chloride chamber and liquefied under pressure. It then flows into a second vacuum chamber where the vacuum is maintained by another pump and temperature drops to  $-140^{\circ}$ . Next, oxygen under pressure is cooled in this chamber, liquefied and poured into a third vacuum chamber

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where the temperature is reduced to  $-183^{\circ}$  by the same method. Air under a small pressure is cooled in the cold of the oxygen chamber and liquefies under this small pressure and runs out as a mobile, slightly bluish liquid, boiling at  $-190^{\circ}$ . The advantage of such a process is the possibility of experimenting at any temperature between ordinary temperatures and  $-190^{\circ}$ . Another advantage in an experimental laboratory lies in low pressures involved. The outfit is too costly and too complicated to be duplicated, however. Liquid air is a common commodity now and almost every large city has its liquid air plant. The plants of L'Air Liquide Society at Montreal, Toronto and Niagara Falls employ the Claude process. The great plants of Norway and Germany employ the Linde process, utilizing the Joule-Kelvin method of cooling, while most of the small laboratory plants employ the same method in the Hampson machine, built by the British Oxygen Company of London. There are also some small Linde machines in laboratories.

If nothing more than the liquefaction of air had been accomplished, the results are worth while, since the best method of separating nitrogen from the oxygen of the air is the process of liquefaction and separation of the components as they re-evaporate. The problem of procuring adequate supplies of nitrogen is becoming one of first rate importance. All vegetation and animal life requires nitrogen for growth. With few exceptions plants cannot take the nitrogen directly from the air, but must get it in the form of nitrates in the soil. Animals cannot take the nitrogen from the air but get it from vegetable matter for the most part. So nearly all life, while requiring nitrogen for growth, must find it in some utilizable form. Unfortunately, it is not very easy to form these compounds of nitrogen owing to the peculiar inertness of this element. Air is a mechanical mixture of nitrogen and oxygen and only under peculiar conditions do they unite to form a compound. A lightning flash does bring about a combination of these two elements which is washed down and in the earth it is transformed into a nitrate which can be utilized by the plant life. But obviously there is not very much formed in this manner. Acting on the hint given by the lightning, a practical process of making a compound of nitrogen and oxygen has been per-

fectured so that by means of an electric arc the same combination is produced. Thus, we have a possible source of nitrogen for fertilization of the soil.

The digging in of animal refuse to rot in the ground is the old way of supplying nitrogen. In this case, bacteria in the soil transform the refuse into ammonia which is oxidized into soluble nitrates. This kind of soil-feeding is slow and inefficient. Fallowing a field is for the purpose of renewing the nitrogen. The world's supply of natural fertilizers is limited and approaching exhaustion, so we turn to the other sources of nitrogen and find the best hope in the air, but, as indicated above, the nitrogen is not available in the pure state but must be "fixed." If coal could be burned in such a way that the nitrogen content could be "fixed" into ammonia as in the gas and coke works, a large source of supply would be available but that is hardly to be expected, at least in the near future, so we turn to the nitrogen of the air. Besides the electrical process mentioned, there are other processes, both electrical and chemical, for fixing the nitrogen once it is separated from the oxygen in the air.

If the air first be liquefied and then re-evaporated in a proper apparatus the two components may be separated to almost purity for each gas. The Claude machine delivers almost pure gases. Wherever power is cheap this industry becomes important. For the supply of nitric acid for the manufacture of explosives a nitrogen supply is needed and here is another important use of the air rectification plants. So, we find these fixation industries in various countries, and they have played an important part in the recent war.

But important as the practical applications of the subject are, the scientific possibilities are more interesting and perhaps more important for future applications. Many interesting phenomena appear if temperatures are lowered only a little. To the inhabitant of a warm country a strong continuous sheet of ice on a lake would be a real novelty to be known only from books and from the accounts of travellers. To us, solid mercury is a novelty, seen only in the very coldest weather of a Canadian winter, yet with solid carbon dioxide we may freeze mercury readily. [Experiment shown]. With temperatures no

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lower than those liquid air supplies, lead becomes like steel. We have only to think of what happens to steel when raised to red heat to complete the analogy—it becomes yielding as lead is at ordinary temperatures. In liquid air, alcohol may be frozen first to an intensely cold syrupy mass, finally to a solid. And many other interesting phenomena appear as the temperature is lowered.

But the cold of liquid air is far from being the lowest limit. It is only about two-thirds of the way to absolute zero. How shall we go lower? For a long time hydrogen defied all attempts to liquefy it but Sir James Dewar finally succeeded. The history of cryogenic laboratories tells of some dramatic events. For example, at the meeting of the French Academy on the twenty-fourth of December, 1877, a letter from Cailletet read as follows:

“I have to tell you first, and without losing a moment, that I have just this day liquefied oxygen and carbon monoxide.

“I am, perhaps, doing wrong to say liquefied, for at the temperature obtained by the evaporation of sulphurous acid, about  $-29^{\circ}$ , and at a pressure of 300 atmospheres, I see no liquid, but a mist so dense that I infer the presence of a vapor very near its point of liquefaction.

“I write to-day to M. Deleuil for some protoxide of nitrogen, by means of which I shall be able, without doubt, to see oxygen and carbon monoxide flow.

“P.S.—I have just made an experiment which sets my mind greatly at ease. I compressed hydrogen to 300 atmospheres, and after cooling down to  $-28^{\circ}$ , I released it suddenly. There was not a trace of mist in the tube. My gases, carbon monoxide and oxygen, are therefore about to liquefy, as this mist is produced only with vapors which are on the verge of liquefaction. The prediction of M. Berthelot has been completely realized.”

At the same meeting the following telegram was read:

“Geneva, December 22, 1877.

“To-day I liquefied oxygen at a pressure of 320 atmo-

spheres, and a temperature of  $-140^{\circ}$ , obtained by means of sulphurous and carbonic acids.

"Signed, RAOUL PICTET."

Roscoe and Schorlemmer in their account of these observations, say:

"It is difficult, on reading the descriptions of these experiments, to know which to admire most, the ingenious and well-adapted arrangement of the apparatus employed by Pictet, or the singular simplicity of that used by Cailletet. The latter gentleman is one of the greatest of French ironmasters, whilst the former is largely engaged as a manufacturer of ice-making machinery, and the experience and practical knowledge gained by each in his own profession have materially assisted to bring about one of the most interesting results in the annals of scientific discovery."

The final liquefaction of hydrogen by Dewar was another such event. After repeated attempts to liquefy this gas in different laboratories, the end was accomplished and a laconic telegram from Dewar in May, 1898, announced to the scientists at Leiden "Hydrogen liquefied." Now, liquid hydrogen is a common sight in cryogenic laboratories.

If we try the method of Hampson and Linde, employing the Joule-Kelvin effect of expanding through a small orifice, we find that hydrogen is heated instead of being cooled. This was the difficulty Dewar had to overcome. He found that if hydrogen is first cooled in liquid air, then the expansion from high pressure produces a lowering of temperature as in the case of air and then the regenerative process may be employed and the hydrogen liquefied at  $-253^{\circ}$ . At this appallingly low temperature air is a solid. A vessel containing liquid hydrogen may have frost collect on it, but this will be air frost, i.e. air that is frozen. If the hydrogen be evaporated at low pressure by a vacuum pump the temperature falls to  $-257^{\circ}$  when the hydrogen freezes solid. By continued evaporation the temperature may be reduced further, to  $-259^{\circ}$ .

Is this the end? Fortunately, there is one more gas, helium, of such peculiar properties that it is still gaseous at these low temperatures. And if cooled to  $-258^{\circ}$ , it may then be

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expanded in the Hampson machine and cooled still further until it liquefies at  $-268.8^{\circ}$ . It, in turn, may be cooled further by evaporation under reduced pressure and the temperature lowered still more. The lowest temperature was obtained by Onnes at Leiden when  $-271.9^{\circ}$  was reached, only a little over one degree from the lowest temperature, but the liquid helium did not freeze. If helium behaves like other gases, it should be possible, by the process of boiling under reduced pressure, to lower the temperature until the liquid freezes. Experiments are in progress at Leiden to complete this work by utilizing a more powerful pump to lower the pressure and helium may be expected finally to succumb. This may be accomplished in the very near future. When we consider that fifty years ago helium was unknown on the earth, we can appreciate the magnitude of the undertaking to prepare some 300 litres of this rare gas for the experiments. The extraction of the gas and its purification occupied nearly three years.

Shall we have reached the lowest temperature when helium is solidified? We cannot answer with certainty, but unless another rare and less easily condensed gas is found, or some entirely new line of attack is developed, it is hardly probable that we shall get down to much less than one degree above absolute zero during the next ten years.

What has come out of this low temperature study save the gratification of a legitimate scientific curiosity? We have learned a great deal about the properties of matter. We have been able to generalize extensively and to see that the condition in which matter is found is largely a matter of temperature. Platinum, mercury, water, air, hydrogen and helium are alike in many respects if taken at the proper temperatures. There are differences, of course, between metals and non-metallic substances.

For specific lines of progress we may mention the subject of electrical conductivity in metals. We have known for many years that at high temperature metals conduct less readily than at low temperature. The low temperature investigations have shown us that this general law obtains down to very low temperatures, but in the region of helium temperatures a new and unexpected phenomenon appears that is bound to throw

light on the mechanism of electrical conduction. At a few degrees above absolute zero, the resistance of a few metals, e.g., tin, lead and mercury, suddenly falls off to practically zero, i.e. the electrons pass through the metal with no evolution of heat as is usual in a conductor carrying a current. This is a remarkable phenomenon. For example, the resistance of lead at  $-272^{\circ}\text{C}$ ., is less than  $1/100,000,000,000$  of what it is at  $0^{\circ}\text{C}$ . Onnes calls this state, super-conducting.

A small coil of lead wire was made and immersed in liquid helium, the ends of the coil being first joined together. A current set up in this coil continued for hours without appreciable reduction. Ordinarily, the current would have dropped to zero in a few thousandths of a second. This is one of the most striking experiments of modern physics and it is no wonder that Professor Onnes speaks feelingly of its success. He said, "I knew the current must be there, but I could believe it only with difficulty even though I had calculated its value."

It seems to be proven beyond all doubt that magnetism is a property of exceedingly small particles of the magnet. For, if a magnet be broken in two, each portion is a magnet and this process may be continued almost indefinitely. It has been thought that the elementary magnets were the molecules, but with the dropping of the molecule from its position of good standing (at least in some solids), this theory must be modified. That the atom is not the magnetic unit is shown by the fact that certain alloys are highly magnetic, when the components are non-magnetic.

Then there is the so-called Law of Curie, which is a statement of a supposed connection between magnetic susceptibility and temperature to the effect that this susceptibility is inversely proportional to the absolute temperature. This law clearly is borne out by experiment in the cases of some substances, but there are notable exceptions, particularly at low temperatures, and a very great amount of work remains to be done. The various theories of magnetism require thorough examination, and experimental investigations are very necessary. Just as there is an ultimate electrical charge, the electron, so it is imagined by Langevin and Weiss that there is an ultimate magnetic quantity, the "magneton..... or unit magnetic moment.

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These magnetons are supposed to be due to the rotation of electrons in their orbits.

A similar theory has been proposed by Parsons, which suggests that the electron itself is magnetic and its magnetism is due to its rotation. Parsons imagines the electron to be in the form of a ring rotating on its axis with high speed. This ring is called, "the magneton," by Parsons. This magneton has the virtue of being easier to visualize. But all of these theories are incomplete and open to criticism. If the magnetic effects are electronic and affected as we know by temperature, we may hope that experiments, carried on at excessively low temperatures where the heat vibrations are very small, will lead to the clearing up of many difficulties. To paraphrase the words of a recent writer we may say that in magnetism we have a field of physics in which investigators have toiled for nearly a century, and all that we have are disconnected facts, a few scattered theories and a feeling of helplessness when we attempt to get a larger view of the facts and theories.

In the atoms of certain of the chemical elements, notably radium, there are changes that are peculiar. Occasionally one of these atoms loses one or more of its elementary charges. These elementary charges leave the parent atom with prodigious speed and cause the phenomena associated under the name radio-activity. These phenomena are electronic in origin and independent of the temperature. This suggests the view already mentioned that the vibrations of the atoms, which we call heat, do not control the motions of the electrons. This has been proved experimentally down to the temperature of liquid hydrogen. It would be interesting to push the experiment further and lower the temperature to the helium region. There is no reason to expect anything new, but there was no expectation of finding a super-conducting state.

One more question whose solution may appear with continued cryogenic experimenting is one raised by the density of liquid helium. We have good reason to believe that the element helium in the gaseous state is monatomic, i.e. its elementary particles are single atoms. Then its inertness, forming as it does no chemical combinations, indicates a comparatively simple structure. When liquefied at  $-268.8^{\circ}$  the density of

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the liquid is .112. This density increases like that of other liquids when the temperature is lowered, but at about 2.35 degrees above absolute zero, this density becomes a maximum and at lower temperatures the density is actually smaller. Thus helium behaves like water at 4°C. where that liquid has its maximum density. This phenomenon needs interpretation and unless further experiments show the incorrectness of the conclusion stated above, we may expect to learn something from the fact that we have a maximum density with such a simple atom. So we may expect more light on all problems connected with atomic and electronic structure by investigation near absolute zero. It is true that in approaching this point we are near one of Nature's ultimates, perhaps nearer than to any other. As we approach the ultimate, new knowledge and interest increase and the horizon widens rapidly.

A. L. CLARK.

Physical Laboratory,  
Queen's University,  
December 20, 1918.

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