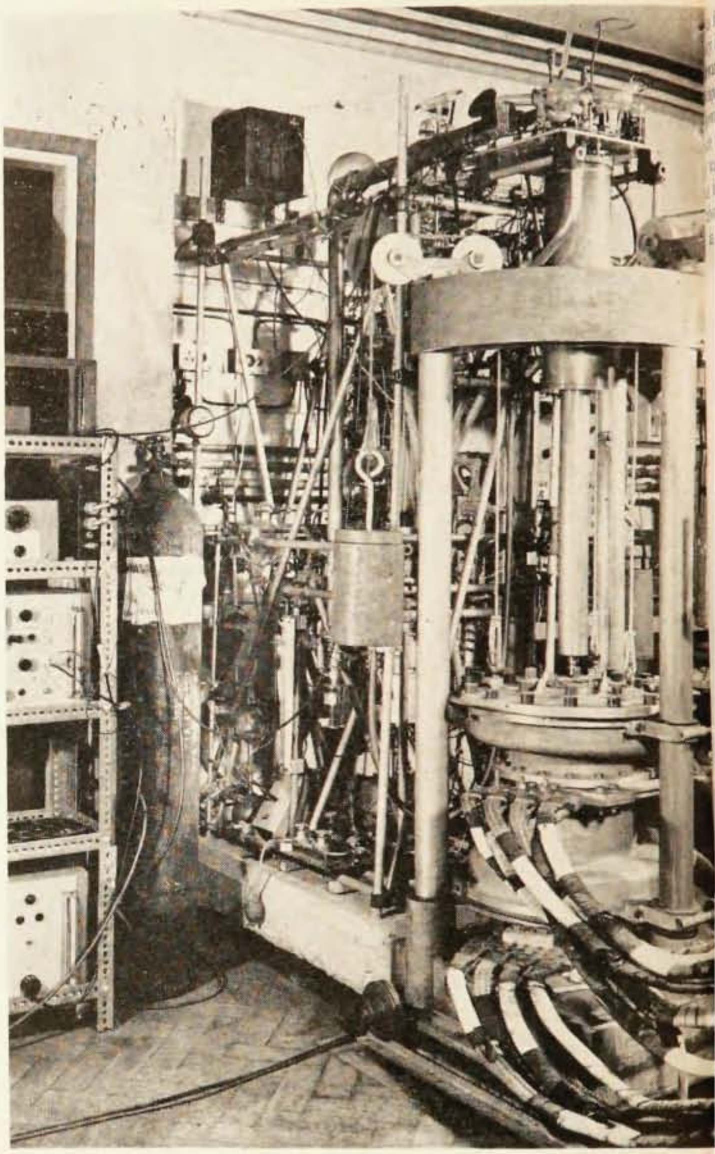
The LOWEST TEMPERATURE in the WORLD

By Nicholas Kurti



DURING the last decade there has developed in physics a strange partnership between the two seemingly distant and unrelated disciplines—nuclear physics and low-temperature physics. Nuclear physics is concerned with the structure of the nucleus and with the very large forces that hold its constituents together. The energies involved in nuclear changes, such as radioactive transformations, are vast and correspond to temperatures of tens or hundreds of millions of degrees. How then could such changes be influenced by ordinary temperatures, let alone by temperatures of only a few hundredths of a degree above absolute zero.

Indeed, only a few years after the discovery of radioactivity, Madame Curie and Kamerlingh Onnes, the founder of the famous Cryogenic Laboratory of Leiden, Holland, showed in a classical experiment that the heat generated by radium during its decay was the same at room temperature as at the very much lower temperature of boiling liquid hydrogen. But, while it is true that the energy liberated in a radioactive transformation and the rate at which this transformation proceeds are unaffected by temperature, there are some other subtle properties of radioactive decay that can be influenced and studied by the application of low temperatures.

Magnetic Moments

MOST atomic nuclei, especially radioactive nuclei, possess a magnetic moment, that is, they behave like tiny magnet needles; one can therefore talk about the orientation of a nucleus in space. When a radioactive nucleus decays, it does not radiate uniformly in all directions; the intensity varies with the direction rela-

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aratus for nuclear cooling at the Clarendon oratory is built around cryostat (enclosed in l Dewar vessel), underneath which is a mag-coil capable of producing about 60 kilogauss a power dissipation of 1500 kilowatts. Also wn are the flexible current leads and pipes ying water for cooling. To the left is the aratus for measuring the very low tempera-s (about one millionth degree absolute) hed in experiments with this equipment.
British Information Services photo

tive to the orientation of the nucleus. This intensity distribution depends on the mode of the radioactive decay, on how the magnitude and the direction of the nuclear moment changes and on the nature of the radiation, and can thus provide useful information about the structure of the nucleus—information not obtainable by the more conventional methods of nuclear physics. Unfortunately these tiny magnets normally point at random in all directions so that, although a single nucleus radiates preferentially in one particular direction, the total radiation emitted by a piece of radioactive material is isotropic. The problem is how to bring order into the orientations of the nuclei, how to make all, or at least most of them point in one particular direction.

It is always possible to force a magnet into a certain direction by means of a magnetic field; but, with our atomic or subatomic magnets this field must be strong enough to counteract the disordering tendency of thermal agitation. Nuclear magnetic moments are very small, and to regiment the nuclei at room temperature one needs the grip of fields that are a million times larger than anything that can be produced. But if one cools the material and thus reduces the state of agitation which all the nuclei possess at room temperature the fields required diminish. They become smaller the lower the temperature, and at a temperature of about 0.01° K they reach values which can be obtained in practice. You will notice that I have given the temperature in degrees K—a scale which has the same size degrees as centigrade but starts from absolute zero instead of the freezing point of water. 0.01° K is about minus 273° C.

Low-Temperature Methods

THE usual methods for producing low temperatures, namely by liquified gases, are of no use for this region. Even liquid helium enables one only to attain about 1° K, and to reach still lower temperatures the so-called magnetic cooling method has to be used. Its principle can be understood roughly by analogy with a more familiar phenomenon, namely the way a gas warms up on compression and its cooling on expansion. Similarly there exist substances—certain paramagnetic salts—which warm up when magnetized and, conversely, cool when the magnetic field is removed. To reach low temperatures with the help of this process the substance is first magnetized at about 1° K, the heat so evolved being absorbed by the bath of liquid helium—rather as the heat of compression of a gas is absorbed by the cooling water of the compressor. After the specimen has been thermally insulated from the liquid helium the magnetic field is switched off and the temperature falls. With suitable substances—some of these are quite ordinary materials like iron alum—it is possible to reach in such a single "magnetic expansion" or demagnetization temperatures of about 0.01° K or even less.

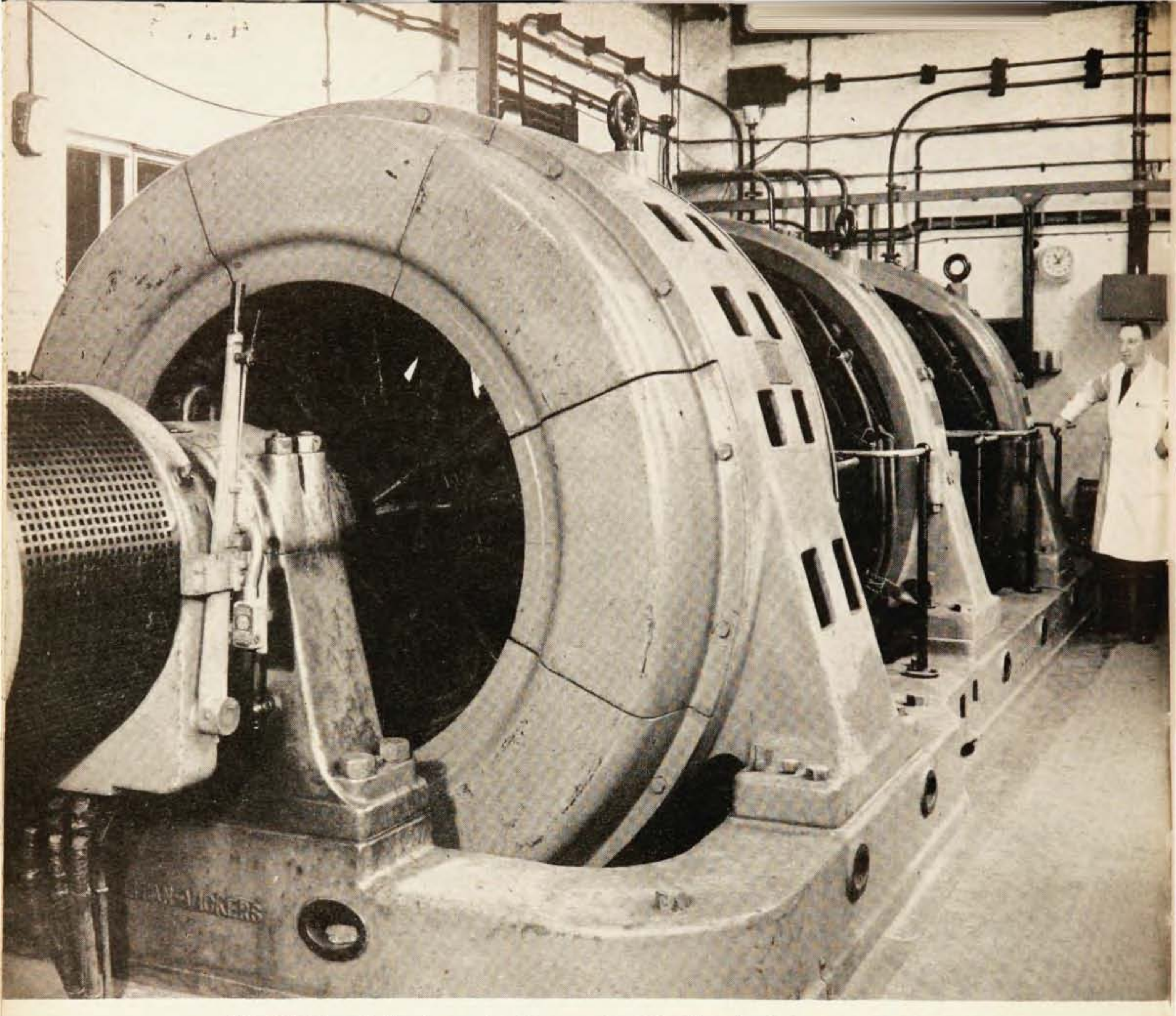
But even at these temperatures, the magnetic fields needed for an appreciable orientation of nuclear magnets are inconveniently large, 50 000 to 100 000 Gauss (the Earth's magnetic field is about 0.2 Gauss). Fortunately, in some substances Nature itself provides such strong local magnetic fields. These fields are due to the magnetic moments of the electrons in the outer atomic shells, and, as was pointed out by Professor Gorter in Leiden and Dr. Rose in Oak Ridge, can, under certain conditions, be used to force the nuclear magnets into an ordered array. One particularly effective method for achieving this had been proposed by Professor Bleaney, and it was with this method that the first successful experiments on nuclear orientation were carried out in September 1951 at the Clarendon Laboratory, Oxford.

Drs. Daniels, Grace, and Robinson cooled a suitable paramagnetic crystal containing some radioactive cobalt to about 0.02° K and found that the specimen emitted less gamma radiation parallel to the orientation of the nuclear magnets than perpendicularly to it. In the eight years since this pioneer work, the study of radioactive decay with oriented nuclei has been pursued in many laboratories all over the world and led to many exciting discoveries such as the dramatic result of the famous Bureau of Standards experiment which, in 1957, almost overnight demolished the law of the conservation of parity.

Valuable Information Obtained

INITIALLY, the main object of nuclear orientation studies was to obtain information about the properties of these nuclei and about the way they decayed. There are, however, more recent applications in which radioactive nuclei of known properties are added in minute quantities to the substance to be studied. The different quantities of gamma radiation emitted in different directions by these give the degree of nuclear orientation from which, in turn, the strength and the directions of the magnetic fields inside atoms can be deduced.

For instance, in strongly magnetic materials like iron, cobalt, or their alloys these internal magnetic fields are due to the same electrons that are also responsible for ferromagnetism. If such a substance is magnetized all the local fields point the same way and the anisotropy of the gamma radiation from the sample, suitably "doped" with some radioactive cobalt gives the strength of the intra-atomic field. Experiments of this kind have already given valuable information about some fundamental properties of ferromagnetic substances.



The 2000 kilowatt, direct-current motor generator at the Clarendon Laboratory provides currents as high as 5000 amperes to energize high-powered magnet coils. *British Information Services photo*

Ordered Array

SO far we have been discussing the use of radioactive nuclei in low-temperature physics, but an equally important part is played by these stable nuclei which act like magnetic needles. We have compared, earlier, magnetic cooling with refrigeration by the expansion of a gas, and we can profitably pursue this analogy a little further. Gas expansion is a powerful method for reducing temperature, but only up to the point where the forces acting between the molecules make them coalesce and the gas liquifies. Something rather similar happens in the magnetic cooling method. It is fairly easy to reduce the temperature until a point is reached at which the forces between the elementary atomic magnets from which a paramagnetic substance is made up become strong enough to counteract thermal agitation. The atomic magnets then "coalesce" into an ordered array like soldiers on parade and further cooling is very difficult. For the commonly used paramagnetic substances the temperature at which this happens is between 0.001° K and 0.01° K. If one could find a substance in which the energy of interaction between the elementary magnets is considerably smaller, this temperature of coalescence would be proportionately reduced. It turns out that a substance whose magnetism is due to the nuclear magnets rather than to the electronic magnets satisfies this condition. This is because the nuclear magnetic moments are about a thousand times smaller than the electronic magnetic moments and hence their interaction energy is considerably less. Unfortunately, the very smallness of the nuclear magnetic moment raises a difficulty. To cool by demagnetization one must first of all magnetize the substance and, as we have seen before, the fields needed in the case of nuclear magnets are impracticably large except at the very low temperatures of the order of 0.01° K. Since one degree K is about the lowest temperature that can be reached by means of liquid helium, nuclear cooling has to be done in two steps.

First the temperature is reduced to about 0.01° K by demagnetization of a paramagnetic salt. The nuclear magnetic specimen is then magnetized and the heat so cooled is absorbed by the paramagnetic stage acting as a "heat-sink" at 0.01° K. Thermal contact between the nuclear stage and the paramagnetic stage is then broken, and on switching off the magnetic field the temperature of the nuclear stage falls.

Sources of Heat Eliminated

NUCLEAR cooling seems a simple enough idea but, as it often happens, many difficulties had to be overcome before the experiment could be carried out. Equipment for the production of intense magnetic fields had to be installed. Various technical problems which are specific to multi-stage processes at these temperatures had to be solved. In designing the apparatus great care had to be taken to provide the nuclear stage with good thermal insulation and to eliminate all sources of heat. The stringency of the conditions to be satisfied can be illustrated by remarking that even a minute amount of heating such as results from a small pin dropping through a height of one-eighth of an inch (a few millimeters) would warm a bulky specimen of several ounces (a hundred grams) from one-millionth of a degree to the starting temperature of one-hundredth of a degree and thereby spoil the experiment.

The first nuclear cooling experiments which owed so much to the genius and imaginative leadership of the late Sir Francis Simon were carried out in 1956 at the Clarendon Laboratory. The sample consisted of a bundle of thin copper wires and temperatures of about ten-millionths of a degree above absolute zero were attained. The temperatures were derived from the magnetic properties of the sample, just as in ordinary magnetic cooling. Since these first experiments the methods and the apparatus have been improved, much useful information about the prospects and potentialities of nuclear cooling has been obtained and, recently, temperatures down to about one-millionth of a degree absolute have been reached.

Nuclear Magnetic Moments

ONE is justified in asking whether there is any good reason for trying to reach lower and lower temperatures. There is, after all, not much physical significance in the absolute value of any temperature. For instance one degree K, which may be regarded as extremely low as far as the ordinary properties of a metal like copper are concerned, is very high when one considers the nuclear magnetic moments in the same metal. One of the main objects of low-temperature research is to reach a temperature region where the system concerned assumes a well-ordered state—that is, the vibrations of atoms due to heat are virtually stilled. In the case of the nuclear moments in solids this happens below one-millionth of a degree absolute and the first object of these experiments is to reach that state. It will then be possible to learn about the nature of the forces between nuclear moments and what their effect is on the ordering process.

It is unlikely that these results will have any immediate practical importance, but they might lead to a better understanding of some subtle characteristics of metals. Speculation about changes that might take place at these extremely low temperatures does not seem to be profitable, and only experiments can show whether, for instance, some of the electrical or magnetic properties of metals undergo some drastic change at temperatures where all the constituents of the substance are in perfect order.

Although, as mentioned before, beating of low-temperature records is a pointless pursuit, one is fascinated by the fact that large temperature regions are traversed in these experiments. This seems paradoxical since we are dealing with temperatures only a hundredth or a millionth of a degree above absolute zero, but it must be remembered that absolute zero is an unattainable limit and that temperature changes should be measured in terms of ratios rather than as differences. Thus the temperature of the sun (6000° K) is about as far removed from ordinary temperature (300° K) in the upward direction, as is the temperature of solid hydrogen (14° K) in the downward direction. Similarly we can compare the range of man-made low temperatures with that of man-made high temperatures. For the former we find, simply by comparing ordinary temperatures (300° K) with those obtained by nuclear cooling (0.000001° K) a ratio of about three hundred million. Taking, on the other hand, 10 million degrees reached in thermonuclear devices as the highest man-made temperature, we find for the upward range a ratio of only 30 000.

Interior of Stars

IT is amusing to go one step further in this comparison of ultra-high and ultra-low temperatures and to consider the highest true temperatures that probably exist in the whole universe. These would occur in the interiors of stars in which elements are being formed by thermonuclear synthesis and could reach about 4 billion degrees—a ratio of 14 million relative to ordinary temperature and still very modest compared with the much larger downward step.

These lighthearted comparisons should not be taken too seriously; but they serve to emphasize the large temperature range that cryophysics covers. And, even if one were to represent the domain of low temperatures as a barren and lifeless desert it would be one liberally dotted with oases of exciting and unexpected physical phenomena.