Physics Research at T.R.E.[1]

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THE NAME T.R.E. is very well known to many physicists and electronics engineers in the United States, and yet few know for what these letters stand. This is not altogether surprising, as the name became almost legendary during the war at a time when most places were known by letters and few bothered to inquire what these letters meant. T.R.E. is known as the research establishment where much of the British fundamental work on radar originated and where the many outstanding radar devices for the Royal Air Force were born. T.R.E. is, in fact, a Ministry of Supply Research Establishment at Malvern, England, and the letters stand for Telecommunications Research Establishment.

T.R.E. was a wartime creation, and many of Britain's leading scientists worked there during the war. The nearest American equivalent was the Radiation Laboratory at Massachusetts Institute of Technology. The wartime team was very mixed and included physicists, mathematicians, radio engineers, and a whole variety of others, such as geologists, physiologists, and zoologists, all with a common love for electronics and its application to wartime problems. Toward the end of the war the British team was augmented by two American groups—British Branch of the Radiation Laboratory, and the American and British Laboratory—so that many American scientists got to know Malvern and to share in the stimulating atmosphere of T.R.E. Thus a widespread friendship grew up as many British workers visited M.I.T. and many American workers visited T.R.E. If one makes a tour of the British university research departments, nearly everywhere one meets old friends who were at T.R.E. I had recently the privilege of visiting a considerable number of American university research departments and again everywhere I met friends who had visited Malvern during the war or whom I had got to know at M.I.T.

As was natural, at the end of the war many of the senior research staff returned to their academic posts which they had left to take up radar research. There were some, however, who felt that the spirit of T.R.E. should be carried on and that the establishment should continue for the purpose of combined research and development. Many felt, too, that in order to retain the keen spirit of the team it was necessary that a fairly large fraction of the effort should, in peacetime, be devoted to fundamental research. It was thus that the Physics Department came into being. A small nucleus of senior wartime research staff stayed on to build up this department, which has now grown into an extensive laboratory with a varied research program. There was no college or university to which this department could be attached as the Radiation Laboratory was attached to M.I.T. and so it naturally remained part of T.R.E. It is an integral part of the main establishment, whose business is still the development of electronic devices for the Royal Air Force. The type of work at T.R.E. and the relation of physics research to it have recently been described in an article in *Nature* (*4*). The present article will be restricted to the work of the Physics Department. I have chosen one or two of the more interesting recent achievements of the laboratory and some of the more difficult problems under investigation in order to give an impression of the scope of the work.

Electronics research. T.R.E. has always been known for the development of new types of electronic circuits, and the group under F. C. Williams produced many excellent electronic devices. Before he left to become professor of electrical engineering at Manchester his now well-known work on cathode ray tube storage for digital computers had been started in the Physics Department. This he has continued with conspicuous success at Manchester, and the T.R.E. group is working in close collaboration with him on this interesting development. It was natural that the new wartime electronic developments should be turned toward instrumentation for scientific research. A typical example of recent work is the Automatic Ultraviolet Absorption Spectrophotometer built for the Medical Research Council and now in-

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stalled in the London Hospital. This instrument enables a doctor to obtain within a few minutes a graphical record of the absorption spectrum of a small quantity of a biological solute without a need for prior knowledge of the absorption of the solvent. Two light paths are used, one passing through the solution and the other through the solvent alone. A stop in one path is varied so that the light is kept equal at the ends of the two paths. The electronic problem is that of providing a servomechanism to drive the stop so as to produce equality and thus to provide direct recording of the extinction coefficient. Various refinements are added, such as correction for the quartz dispersion law and a variable speed drive, controlled by the complexity of the spectrum being observed. By use of a "constant error" principle the machine is automatically made to run quickly through the dull parts of the spectrum and to slow up and record carefully the interesting peaks. The instrument has been in operation for about nine months now and has been successfully used by biochemists in their work on synthesis of complex organic substances, including some of the vitamins. They report that they have been able to do months of work in a few days by using the instrument and that in spite of its very complex electronic circuits it has given no trouble in operation—thus confounding the skeptics!

Another example is the application of electronics to the control of astronomical telescopes. Some preliminary experiments have successfully been carried out in conjunction with the Royal Observatory, Greenwich (*5*).

Millimeter waves. It was natural, after the rapid development of centimeter waves during the war, that attention should be turned to even shorter wavelengths, and the millimeter wave band is now being explored. For some time klystrons have been made in the laboratory that operate successfully at wavelengths around 8 mm. Surprisingly high powers have been achieved, and valves are now regularly made which give continuous wave outputs of the order of 100 milliwatts at 8 mm. Encouraged by this, and in spite of considerable mechanical difficulties, klystrons have been designed for a wavelength of 5 mm. A few have been made that give outputs of the order of 10 milliwatts.

If one examines a piece of waveguide scaled down for a wavelength of 5 mm, it soon becomes clear that it will be extremely difficult to transmit much power along a guide of such small dimensions. One is therefore led to examine optical methods of transmission using lens systems, etc., and to investigate the properties of optical measuring instruments at these wavelengths. Some curious problems arise as one is working more or less between the Fraunhofer and Fresnel conditions for diffraction. As a beginning, a Michelson Interferometer has been made, and thus has turned out to be a most useful instrument for the accurate measurement of wavelengths in the millimeter region. Now that sources giving considerable power are available various investigations of the properties of materials at millimeter wavelengths are being undertaken.

Semiconductors. A good many laboratories with an electronic background have become interested in semiconductors of late. The substances with which most of the work has been done in this laboratory are those of the PbS, PbSe, and PbTe group. The reasons for this are twofold. These substances form an intermediate group between the semiconductors like germanium and silicon and the ionic types like the phosphors. Moreover, they have the remarkable property of being photoconductive in the infrared and are thus useful in infrared research, which will be discussed later.

There has been a considerable difference of opinion between various workers as to the value of the energy gap between the "full" and "conduction" bands for these substances. One way of measuring it is to examine the absorption spectrum to determine the "lattice edge" due to electronic transfers between the bands. This experiment turns out to be surprisingly difficult because of the very high reflectivity of these substances. A. F. Gibson has, however, recently been able to measure the absorption spectra of PbS, PbSe, and PbTe between 1 μ and 12 μ and has shown that the absorption edge for PbS corresponds to a gap of over 1 electron volt and not to the much smaller value of 0.4 ev postulated by some workers. For PbSe and PbTe smaller values are found, but none as low as 0.4 ev. He has also found some very curious features in these spectra in the form of long wave absorption "tails," which are not yet understood.

The corresponding group of bismuth compounds, Bi_2S_3, Bi_2Se_3, and Bi_2Te_3, has also been recently investigated. These behave in exactly the same way. They are photoconductive in the infrared, but the long wave cut off occurs in each case at a shorter wavelength than for the corresponding lead compound. Their behavior in the presence of oxygen is also very similar.

The mechanism of photoconductivity in these substances is not yet understood and provides one of the most interesting puzzles in solid state physics at the moment. A good deal of work is in hand with the object of shedding new light on this problem.

Infrared research. The work on the PbS, PbSe, and PbTe group has led to the development of extremely sensitive detectors of infrared radiation, which have the advantage over the usual thermocouple of responding very quickly. These substances, in the form of thin microcrystalline layers, become photoconductive when treated with oxygen and are very sensitive to quite small quantities of infrared radiation. Unfortunately, the range of wavelengths at which they are sensitive is limited. PbS cooled to liquid air temperature will work satisfactorily out to a wavelength of 3.5 μ (*3*). Some PbTe cells recently made at T.R.E. are, however, about 100 times more sensitive than the best commercially available thermocouple out to 5.5 μ and are quite good to 6 μ when cooled to liquid air temperature. A small number of these cells have been given to workers engaged in high resolution spectroscopy, and some fascinating new results have already been obtained both in England and in the United States.

In collaboration with the Admiralty, measurements have been made of the atmospheric transmission in the infrared over long paths in the lower atmosphere. It has been possible to identify the absorption due to deuterium hydroxide (*1*) and some other rare gases in the atmosphere.

Radio meteorology. One interesting application of radar to purely scientific problems is its use to study the formation of rain. There has just been completed a very interesting piece of research in this connection. It started, in purely utilitarian fashion, in an attempt to determine the best kind of radar set with which to equip aircraft to help them avoid dangerous clouds. It soon developed into a most interesting study of rain formation. If one measures the absolute echo intensity from falling raindrops (or ice flakes) at three different wavelengths one can, by applying some fairly complex theory on scattering of radio waves by small obstacles, obtain a measure of their size and concentration (*2*). One can thus study the variation of size and density of raindrops with height and watch the drops being formed near the freezing level. Two interesting facts emerged. Under usual conditions in Britain, most rain starts as falling ice crystals, which melt as they fall through the freezing level. Second, it sometimes rains up above when no rain is falling at ground level—many would say this was just as well!

Low temperature physics. One of the great advantages of the physics laboratory at T.R.E. is that it shares the facilities of the very fine workshop built during the war. In the past year such things as double prism infrared spectrometers and a hydrogen liquefier have been made. The latter came into operation in May, 1949 and has enabled measurements on semiconductors to be extended down to hydrogen temperatures. At the moment a Collins type of helium liquefier is being constructed. Apart from the compressor this is all being made in the workshops. It is hoped by this means greatly to extend the low temperature facilities of the laboratory over the next year or so.

Theoretical physics. It has always been felt at T.R.E. that the work of a physics laboratory is greatly strengthened by having an active theoretical team working in the laboratory itself. The theoretical work is now mainly devoted to two wide subjects: propagation of radio waves, particularly in electron clouds, and quantum theory of solids. The former ties in closely with the work on millimeter waves, and G. G. Macfarlane has recently developed a powerful method of dealing with problems involving electron space charge. It has been used to study propagation of amplifying waves in electron streams and has also given a new method of obtaining the oscillation criterion for a magnetron. On the quantum theory side, the very difficult problem of working out the electronic wave functions of the PbS group is being undertaken, and much theoretical speculation has taken place on the mechanism of photoconductivity in the infrared.

It is hoped that these notes will serve to give some idea of the varied scope of the research program of the laboratory. The work is partly supported by the Ministry of Supply as part of the defense research program and partly by the Department of Scientific and Industrial Research. The work is carried on in close collaboration with a number of British universities, and it has been a great privilege and stimulus to us to exchange news and ideas with a number of American universities who are working on similar problems.

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