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CURRENT PROGRESS IN X-RAY PHYSICS[1]

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INTRODUCTION

WHILE the title of this address covers a great deal of ground, it is really intended to limit the field rather than to widen it. Current progress in x-rays might well include the great advances in the application of x-rays to medicine, both in diagnosis and in therapy. Likewise it might include x-ray engineering. In that field there is rapid progress in the use of x-rays for testing engineering materials and also in the design and improvement of x-ray apparatus. While current progress in x-ray medicine and x-ray engineering are of vast importance, it is obvious that they can not be included in this address. Likewise, x-ray chemistry and mineralogy, by which I mean the use of x-rays in the study of the structures of molecules, either in fluids or in crystals, would take us much too far afield. I must therefore consider only topics that are clearly x-ray physics.

Even within this limit the field is far too large to be covered uniformly. So I shall illustrate the nature of current progress in x-ray physics by taking as an example a still more restricted field within it, namely, the physics of x-ray emission.

HISTORY

To bring out the significance of current progress in x-ray emission, let us first consider some familiar landmarks in its history. The most familiar of all, probably, is the famous series of spectra photographed by Moseley in 1913 and shown diagrammatically, with extensions to lighter and heavier elements than those used by Moseley, in Fig. 1, after Siegbahn. Moseley's spectra showed such a regular-

[1] Address of the retiring vice-president and chairman of the Section of Physics, American Association for the Advancement of Science, Boston, December, 1933.

ity of progression, from each element to the next, as to give the first definite proof of the importance of the atomic numbers. And the similarity of the spectra of the different elements was the first definite proof of the similarity of the structures formed by the inner electrons in all heavy atoms.

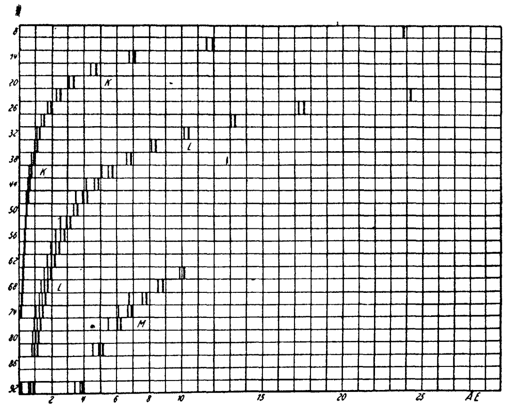

Fig. 1

Barkla, five years before Moseley's work, had found the x-rays from these same elements to be very regular in their properties. Moreover, he had come so near to the concept of atomic numbers as even to insist that the atomic weight given by chemists for nickel must be wrong, because nickel was out of order in the sequence of atomic weights, while its x-ray properties were just as regular as those of any other element. The factor that made it possible for Moseley to supplant atomic weights with atomic numbers was the increase of accuracy given by the Bragg x-ray spectrometer. And the factor enabling him to prove the similarity of the inner-electron structures of the elements more definitely than Barkla had proved it was the increase in resolving power for x-ray spectra, made possible by the same new apparatus.

And so it has been with x-ray spectra ever since. The next great advance was the long and careful series of researches by many physicists, especially by Siegbahn and his collaborators, extending Moseley's work in both directions along the scale of atomic numbers, and persistently improving the accuracy of the measurements, and attaining still higher resolving power to separate the lines into their components and to discover new lines.

In all this work, as in Moseley's first survey, the progression of each line from element to element was found to be very regular. Nevertheless, on careful theoretical analysis, some less regular aspects appeared. This happened when the frequencies of the lines were calculated as term differences, as in the optical series, and the term values were plotted against atomic numbers by Bohr and Coster, as in Fig. 2. Here the higher term values showed the same regularity of progression that Moseley had found for the line frequencies; but the graphs for the lower terms showed sudden changes of slope. These were interpreted in terms of changes in the structures of the atoms. More specifically, if we imagine ourselves building up a heavy atom by increasing the nuclear charge by a proton at a time, and letting new electrons fall in as they please, each bend in the graphs marks a point in the sequence of elements where the filling of some electron shell is completed and the next one begins. 57, for example, is the beginning of the rare earth group.

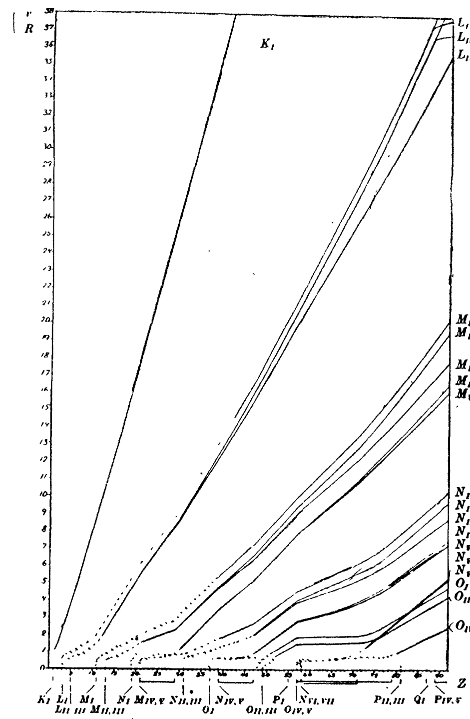

Fig. 2

To be sure, the bends in these graphs were not the only evidence we had on the filling of the shells. Chemical data and the spectroscopy of ordinary light confirmed these conclusions. But x-rays were one of the most important lines of evidence; and moreover, when any shell was once filled, it became buried under succeeding shells and got out of reach of chemistry or ordinary light; so for heavier elements we had to keep in touch with each buried shell by means of x-rays.

The regularity of Moseley's spectra, on which his discoveries depended, was apparent with measurements to 3 significant figures. The very slight departures from perfect smoothness, which were due to the outer electron shells and which enabled Bohr and Coster to distribute the electrons among them, became apparent with the next significant figure or two. So naturally, one of the present lines of progress is toward still higher accuracy. All the strong lines are now listed to 5 or 6 significant figures, and a few even to 7. And on the theoretical side, our descriptions of the electron shells are being made more specific than mere numbers of electrons, as they take the form of wave-mechanical electron distributions.

CURRENT PROGRESS IN WAVE-LENGTHS

Research within the atoms, however, includes not only the determination of their structures, but other questions also. For example: Now that the electrons are placed, what holds them there? What forces act between them; or, if we must not talk of anything so anthropomorphic as forces, what relations exist between them, and what happens when you disturb these relations? For the outer electrons there are many lines of evidence on which to answer these questions; for the inner there are x-rays and other high-energy rays—all of them available in x-ray laboratories.

A continuation of previous wave-length researches, that ought eventually to yield much valuable information on these new questions, is the extension of x-ray spectra to longer wave-lengths. This development was given a great impetus only a few years ago by the discovery by Compton and Doan of a method of using ruled gratings for x-rays, instead of crystals. Where the longest wave-lengths attainable with crystals were around 20 or 30 Å, this new method, in the hands of Thoraeus and Siegbahn, Dauvillier, Osgood and others, has extended the spectra up into the hundreds of Ångstrom, where they merge gradually into the ultra-violet. In fact in this new region most of the lines would be classed at once as ultra-violet, but some others show the Moseley progression characteristic of the older x-ray region.

These spectra are of a type intermediate between x-rays and ultra-violet in other ways also. The spectra emitted by solids in this region show lines; but their lines are diffuse, and are thus intermediate between the sharp lines of the older x-ray region and the completely diffuse spectra of most solids in the visible. And in theory also these lines are intermediate between ultra-violet and x-rays, being due to transitions between the outer electron states, familiar to students of the ultra-violet, and the inner ones associated with x-rays. Eventually these spectra ought to tell us a good deal about such transitions, when their theory catches up with experiment.

Another field of wave-length researches is on a large class of lines in the older x-ray region, called non-diagram lines because they are not in the diagrams of spectral terms by which Bohr and Coster made their great advance in the theory of atomic structures. To see the significance of the non-diagram lines, let us first take a closer look at a Bohr-Coster diagram for a single element, for example, the one for tungsten as replotted by Siegbahn and shown in Fig. 3. This is obviously a Grotrian diagram for a system of doublets, much like those of the optical spectra of the alkali metals. The S terms are in the left-hand column, the P's next, then D's and F's, as usual. The chief difference is that it is inverted, in the sense that here the electron shell nearest to the nucleus, namely, the K, appears at the top of the diagram rather than the bottom. The reason for this, however, is simply that the energy represented by the point K is not energy given to the atom by putting an electron into the K shell, but by taking one out of it. Placing K at the top, therefore, simply means that it takes more energy to take an electron out of the K shell than out of any other.

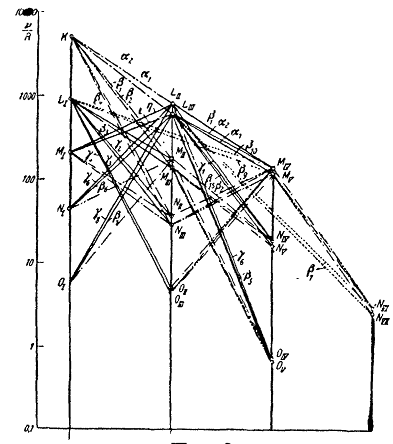

FIG. 3

With this fact in mind, the line drawn downward from K to L_{II}, for example, indicates a release of energy when the atom changes from a state of K ionization to L_{II} ionization, while the actual electron transfer is in the other direction, an L_{II} electron dropping into the K vacancy.

By the usual selection rules, taken over from optical spectra, every electron transfer ought to go between adjacent columns, changing the azimuthal quantum number by ± 1. And evidently most of them do so. In a few cases, however—and these constitute a limited class of non-diagram lines—the change is by 2 units. We have here, for example, the transitions from L_I to M_{IV} and M_V; and the transition from L_I to M_V, as a matter of fact, changes the inner quantum number also by 2 units. The first two non-diagram lines of this class were found as long ago as 1916, by Dershem, and such lines have often been explained as quadrupole radiation; but it is only recently that this explanation has taken a quantitative form, in the hands of Segré. This advance is a good confirmation of some fundamental postulates of the theory of radiation, which predict that quadrupole radiation should be more prominent in x-ray spectra than in ordinary light.

Another class of non-diagram lines are some components of the very strong diagram lines, discovered by van der Tuuk, in such elements as iron, in which the valence shells are incomplete and have high multiplicities. Apparently these lines are caused by coupling between the valence shells and the x-ray shells. This coupling changes x-ray levels from doublets to higher multiples of a peculiar sort, looking like doublets with low resolution, but having each term widened or split when the resolution is increased. These multiplets ought eventually to give valuable information on the coupling between these shells.

Most of the non-diagram lines, however, can not be explained at all in terms of these energy levels; and while some of them were discovered by Siegbahn and his collaborators as far back as fifteen years ago, there are still many new non-diagram lines being discovered every year. To explain them, there are at present two theories. One, due to Wentzel, is that any such line is due to ionization of two inner electron shells at once, followed by a single electron transition like that of one of the diagram lines. The other theory, due to Richtmyer, is that such a line results from a different sort of double ionization, involving an inner shell and an outer one, followed by a two-electron jump filling them both. Wave-length measurements are adduced by the advocates of both theories as confirmatory evidence, without as yet reaching an agreement either way.

INTENSITIES

Wave-lengths, however, are not the only data obtainable from a line spectrum. Other data of coordinate importance are the intensities of the lines. From the theoretical aspect, just as wave-lengths tell us about electrons in their stationary states, intensities tell us about their transitions. As noted already, we now have a great deal of accurate information about the stationary states, but our knowledge of electron transitions is still very incomplete. This difference, indeed, is due primarily to a corresponding difference in the accuracy of present data on wave-lengths and intensities: wave-length data now call for 7-place logarithms, but intensities have not yet graduated from the slide-rule class.

At that, however, intensity measurements have already accomplished a great deal. In their most rudimentary form, that of merely looking at spectrograms and seeing which lines are strong and which are weak, they established some very fundamental laws, notably the selection rules. The advance of intensity research from rough estimates to real measurements was made first by W. H. Bragg and W. L. Bragg, when they measured the intensity ratio of the $K\alpha$ doublet of rhodium, which is like that of tungsten, shown as the transitions K-to-L_{II} and K-to-L_{III} in Fig. 3 (p. 193). This ratio they found to be 2-to-1, like the doublets in the optical spectra of the alkali metals. Further measurements of line intensity ratios, by Duane and his collaborators, and by S. K. Allison, Jönsson and others, revealed other extensions of the optical sum rule to the x-ray series. But there are some notable exceptions. For example, there is a doublet in the L series corresponding exactly to $K\alpha$, namely L_I-to-M_{II} and L_I-to-M_{III}. This doublet has apparently just as clear a reason to be 2-to-1, but its intensity ratio is actually nearer 3-to-2 in the elements for which it has been tested. In many measurements of line intensity ratios there are great difficulties of technique; but in the hands of Allison, von Hevesy and many others this field is making rapid progress.

On the theoretical side, intensity ratios present many unsolved problems. For the diagram lines these appear to be largely problems of quantitative calculation and on them notable progress has been made recently by Pincherle. For the non-diagram lines, however, aside from the quadrupole lines and van der Tuuk's higher multiplets, even the underlying principles are in doubt, because we do not know whether to ascribe these lines to Wentzel's double ionizations followed by single electron jumps or to Richtmyer's double jumps. As Druyvesteyn and others have shown, Wentzel's theory agrees with experiment on many points about intensities as well as wave-lengths. On the other hand, one of the most serious obstacles to this theory comes from the intensity field, in a measurement of the excitation potential of one of these lines in copper, by DuMond and Hoyt, that seems definitely to prove the excitation potential too low for the required double ionization. Nevertheless, Richtmyer's double-jump theory also has its obstacles in the intensity field, among them being a theoretical one found by Langer, that the interaction energy of the two jumps appears too low to predict double-jump lines of observable intensity. Altogether, it seems still too early to decide between these theories. Possibly both may be correct, some lines being explained by Wentzel's theory and others by Richtmyer's.

These researches just reviewed all relate to ratios of intensities of different lines and therefore give information on the ratios of the probabilities of their different transitions. There is, however, another type of intensity research, with another objective. This is on the intensity of any one line as a function of the voltage on the x-ray tube. Its objective is to test the laws of interaction of atomic electrons and cathode rays. More specifically, as the voltage on the tube increases, the intensity of any x-ray line changes in proportion to the number of atoms ionized in the inner shell responsible for that line. In measuring the intensity of any line as a function of tube voltage, therefore, one measures the probability of impact ionization of an inner electron shell as a function of the kinetic energy of the cathode ray before the impact.

Similarly in the continuous emission spectrum, the intensity at any given wave-length, considered as a function of tube voltage, measures a probability of interaction. But while the interaction measured by a line intensity is an ionizing interaction, between the cathode ray and an atomic electron, that measured by the continuous intensity is a radiating interaction, between the cathode ray and the atomic nucleus.

Considering either of these intensities as a function of cathode-ray energy, for directness of theoretical interpretation all the impacts involved in any one measurement must of course occur at the same energy. This condition, however, is never satisfied in a thick block of metal, such as we generally use as a target for cathode rays, but only in an extremely thin film. Measurements with such extremely thin targets involve special techniques of various sorts, and were first made about 5 years ago by several observers independently; for continuous spectra by Duane, by Kulenkampff and by Nicholas; and for line spectra by Clark, Hansen, Yeatman, and me, and by Lorenz.

In spectra of both types, the theories then available were found to be definitely incorrect. For continuous spectra, rapid progress in the theory was then made by Sommerfeld, Sugiura and Eckart, all using wave mechanics. In Fig. 4, for example, we have some theoretical graphs plotted by Sommerfeld, with experimental points from Kulenkampff's data. The ordinates here are continuous-spectrum intensities from a thin target of aluminum, all for the same wave-lengths but for rays emitted in different directions. The graph marked "40°," for example, is for rays emitted at 40° from the direction of the cathode rays; and the other graphs relate to other directions in the same way. In all these graphs, the abscissas are tube voltages, or cathode ray energies, the left end of the scale being the excitation voltage of the wave-length used. In each graph, the first experimental point was known to be much too low, because the resolving power was not sufficient to exclude some wave-lengths excited only at higher voltages. Neglecting these first points, however, the decrease of intensity with increasing voltage is represented by Sommerfeld's theory much more exactly than by any previous one. In other respects, also, this theory compares very favorably with Kulenkampff's measured intensities; and on polarization such parts of it as have yet been tested are confirmed, at least approximately, by Duane, Kulenkampff, Ross and Cheng.

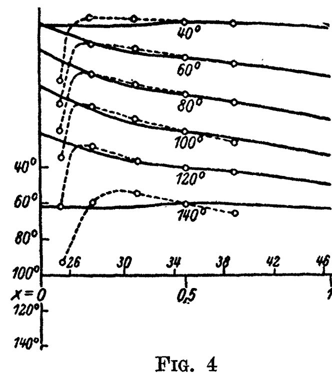

FIG. 4

While these continuous-spectrum intensities measure probabilities of radiating interactions between cathode rays and atomic nuclei, the line intensities, as noted above, measure ionizing interactions between cathode rays and atomic electrons. And here also, much progress has been made since the first thin-target work of five years ago. The next measurements of these interactions, as a matter of fact, were not made by x-ray methods, but by direct measurements of ionization in gases. Among these I should like to call attention especially to some data on helium, since helium contains only one electron shell and is therefore especially simple in theory. Some of the results for helium are shown in Fig. 5. The continuous graphs here represent theoretical equations, while the data shown by the dots are a part of a series running well above the range of voltage covered by these theories, and were taken by P. T. Smith in 1930. The abscissas are voltages, or cathode-ray energies, expressed in terms of their natural unit, the K ionizing potential V_K. The ordinates are probabilities of ionization, or equivalent effective cross-section areas, also expressed in terms of a rather natural unit, the area $\frac{2\pi e^2}{V_K^2}$.

The contrast between the theories shown here is obvious. The classical theory is very far from the data, even though it takes account of all the significant factors known to classical quantum theory, such as the orbital motion of the atomic electrons before impact and the effects of nuclear attractions, both on the atomic electrons and on the cathode rays. On the other hand, Massey and Mohr's theory, and Wetzel's, both of which are based on wave mechanics, are really good approximations.

For ionizing cross-sections taken from line intensities, in the x-ray region, Fig. 6 shows some data on silver obtained recently by Hansen, Duveneck and the

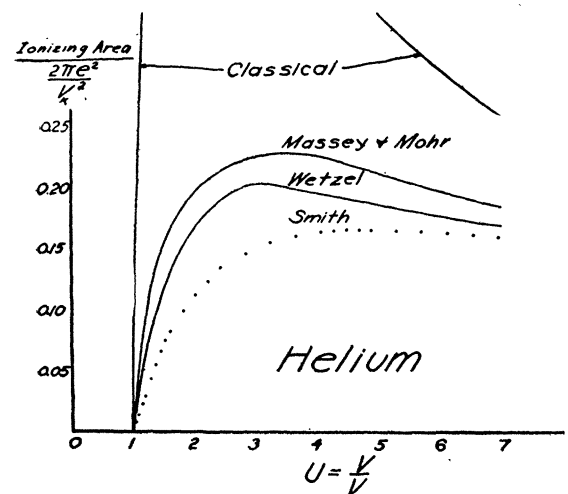

FIG. 5

author. The atomic electrons here are those of the K shell only, as in helium. The significance of the abscissas and ordinates are also as in the helium graphs, except for the fact that the ionization probabilities, or areas, are expressed here in arbitrary units, equating the theoretical values to the experimental at the highest voltage. This procedure is adopted because the absolute values are not known so accurately for silver as for helium. All the theories, however, predict that they would be about a million times smaller for silver than for helium, because their natural unit ($2\pi e^2/V_K{}^2$) is that much smaller; and recent data taken by J. C. Clark confirm this prediction. So the units of the graphs on this slide are probably not very seriously different after all.

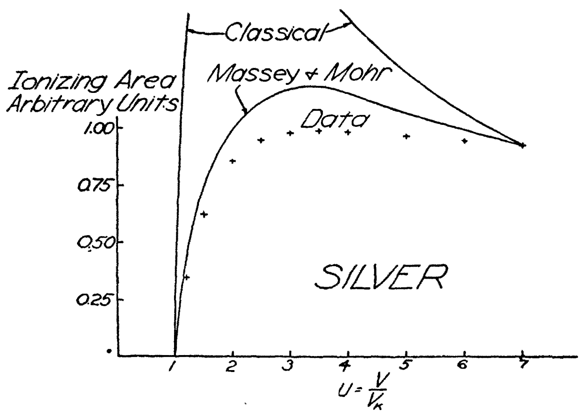

FIG. 6

Evidently, for silver, as for helium, the wave mechanical theory is far better than the classical. Regarding possible differences between the two wave mechanical theories, Wetzel's theory and Massey and Mohr's, the evidence for silver is not yet at hand. Both of these theories require very laborious computations, and I wish to express here my most cordial thanks to Professor Wetzel for starting such computations on his theory, as well as to Professor Massey and Mr. E. H. S. Burhop for actually obtaining the figures for the graph we have before us.

For electrons in shells other than the K, some data have been obtained by Coster and van Zuylen on the L electrons of tungsten, and by Pockman, Kirkpatrick and me on those of gold. The general character of the interactions of these L electrons with cathode rays is much like that of the K electrons, though they differ quantitatively, both from the K electrons and among themselves. These differences would be quite inexplicable by any classical theory; but Goldstein has shown that wave mechanics predicts differences, though whether it predicts them correctly is one of the numerous questions that still lie before us.

In short, this branch of intensity research is now at a stage of evolution that wave-length research had reached about fifteen years ago, when the Ritz combination principle had just been extended to the inner electrons, but nobody knew how many electrons there were in each orbit. For intensities, now, the wave mechanics has just been extended to the interactions of the inner electrons with cathode rays, at least as a good first approximation, but the theory is by no means complete. To date it is based on the first term of Born's perturbation series, with the second considered only in purely qualitative corrections by Massey and Mohr. Much development is therefore needed there. And while the data for silver and helium are much alike, their differences will give us valuable information. The effects of relativity should be much greater in silver than in helium; and also silver contains other electrons, outside the K shell, which must exert an influence, both by the screening effect and by changing the system of orthogonal functions with which one must calculate. Thus the differences between these elements or with others to be tested later will be most significant as a test of the way in which the wave mechanics handles the problems of relativity and of many electrons. Since the contrast between wave mechanics and classical theory is especially great here, and the data decide so clearly between them, it is reasonable to expect such data to be of still further use as a proving ground for theories attempting greater accuracy.

Indeed, considering the broader field of x-ray emission as a whole, it is evident that intensity measurements have a great deal to tell us about the interactions of electrons with one another and with nuclei, and their story has only just begun.

THE REST OF X-RAY PHYSICS

The progress in the physics of x-ray emission, which I have just sketched in outline, is typical of x-ray physics as a whole. Absorption, refraction, scattering, the Compton effect and other branches of x-ray physics present the same variety of researches, ranging from extreme refinements in the study of familiar phenomena to preliminary explorations of new ones.

The most unexplored field in all x-ray physics, however, lies in the direction of extremely high voltages. Coolidge, Lauritsen, Tuve, Lawrence, van der Graaf and their collaborators have already shown the way to this new field and found plenty of new rays there. Thus far, the new rays are all of one type, continuous spectra. But with what we now know of nuclear excitations and disintegrations by positive rays and of nuclear excitations at least by beta rays, there is no telling what may be found in this new field.

Altogether, x-ray physics includes not only the old field of wave-length research, now pushing on from its fifth significant figure to its sixth and seventh, and such newer fields as intensities, now trying for the second or third figure, but even such a very new field as this one of high voltages, where the first figure is still unknown.

SCIENTIFIC EVENTS

THE BRITISH DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH

ACCORDING to the annual report of the British Department of Scientific and Industrial Research, issued recently, the grant of £1,000,000 made by the government in 1917 for the encouragement of industrial research has become exhausted. The fund has been used by the department for assisting the formation of cooperative research associations in various industries, maintained partly by grants from the department and partly by subscriptions from industry. Though the "million fund" is no longer available the department's grants are now being made from its parliamentary vote.

A large part of the report of the Advisory Council of the department, signed by Lord Rutherford, is devoted to a survey of the research association scheme and to summarizing the results of the experiment. The expending of the million fund has attracted a total industrial contribution of £1,750,000, and at the moment the state is contributing £65,000 a year and industry £170,000 a year towards the support of a group of nineteen research associations, which include in their membership some 5,000 firms.

Striking examples are quoted to illustrate the enormous savings that have accrued from research work in various large industries. The report points out that the annual sum of less than £250,000 is trivial in relation to the interests involved and the possibilities awaiting realization. The basis on which many of the research associations are working is said to be hardly commensurate with the size of the industries they serve.

Work in progress is carried on in the department's own establishments and in the laboratories of research associations. For example, work in progress at the Department's Building Research Station includes the study of the most economical means of warming a house, investigations on wall plasters, on the problem of damp walls, on painting on cement and plaster, and on the deterioration of bricks.

The work of the Food Investigation Board of the Department is said to be meeting with considerable success in improving the quality of foodstuffs and in eliminating waste by better methods of transport and storage.

The Wool Industries Research Association has found a new process for making wool unshrinkable by the treatment of the wool fibers in bulk before they are spun.

Work for the automobile industry included research on the problem of cylinder and piston wear, which involved 360 distinct engine tests and 15,000 measurements. Besides this work, the Research Committee of the Institution of Automobile Engineers is carrying out investigations on the wear of valves and valve-seats, big-end bearing problems, lubricating oil pumping, and oil consumption. During the year the responsibility for road research has been transferred to the department from the Ministry of Transport. Researches on road tars are being carried out at the Chemical Research Laboratory. Work on motor-car headlights at the National Physical Laboratory has led to a method for determining the light distribution which should be aimed at for a headlight beam.

The report states that many of the researches of the department have a direct bearing on public health. Chief among these is the work of the Water Pollution Research Board on water supplies and the prevention of pollution. A complete survey is being made of existing knowledge regarding the solvent action of water on lead. The effect of electric currents in leaden waterpipes on the lead content of the water is also being investigated. Work is also being done on water-softening processes.

At the request of the Home Office, the department has arranged for an investigation to produce more efficient respirators for use in industrial processes as a protection against the inhalation of dust.