Physics 1907

ALBERT ABRAHAM MICHELSON

<<for his optical precision instruments and the spectroscopic and metrological investigations carried out with their aid>>

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Presentation Speech by Professor K. B. Hasselberg, member of the Royal Swedish Academy of Sciences*

The Royal Academy of Sciences has decided to award this year's Nobel Prize for Physics to Professor Albert A. Michelson of Chicago, for his optical precision instruments and the research which he has carried out with their help in the fields of precision metrology and spectroscopy.

With untiring eagerness and, it can truly be said, with brilliant results, work is forging ahead today in every field of research in the natural sciences, and new information of ever greater significance is accumulating every day in unprecedented profusion. This is especially true in the case of the exact sciences - astronomy and physics - in which fields we are now obtaining solutions to problems, the mere mention of which up till a short while ago had to be regarded as unreal as Utopia itself. The reason for this gratifying development may be found in improvements in the methods and means of making observations and experiments, and also in the increase in accuracy brought about by these improvements in the quantitative examination of observed phenomena.

Astronomy, the precision science *par excellence*, has not only thus acquired whole new branches, but has also undergone in its older parts a transformation of more far-reaching significance than anything since the time of Galileo; and as for physics, it has developed remarkably as a precision science, in such a way that we can justifiably claim that the majority of all the greatest discoveries in physics are very largely based on the high degree of accuracy which can now be obtained in measurements made during the study of physical phenomena. We can judge how high our standards in this respect have risen from the fact that, for example, as recently as the beginning of the last century an accuracy of two to three hundredths of a millimetre in a measurement of length would have been regarded as quite fantastic. Today, however, scientific research not only demands but achieves an

* Owing to the decease of King Oscar II two days earlier, the presentation ceremony had to be cancelled. The speech, of which the text is rendered here, was therefore not delivered orally.

accuracy from ten to a hundred times as great. From this it is obvious how fundamental is the importance which must be attached to every step in this direction, for it is the very root, the essential condition, of our penetration deeper into the laws of physics - our only way to new discoveries.

It is an advance of this kind which the Academy wishes to recognize with the Nobel Prize for Physics this year. Everyone is familiar with the significance and scope of the uses to which the telescope and the microscope can be put as measuring instruments in precision physics; but a limit to the efficiency of these instruments has been reached, a limit which cannot be exceeded appreciably, for both theoretical and practical reasons. Professor Michelson's brilliant adaptation of the laws of light interference has, however, perfected a group of measuring instruments, the so-called interferometers, based on those laws, which previously only had occasional uses, to such a degree that an increase in accuracy in measurement of from twenty to a hundred times what can be achieved with the best microscopes has been brought well within our grasp. This is due to the fact that, owing to the peculiar nature of the interference phenomena, the desired value - usually a length is measured -can be obtained in numbers of wavelengths of the type of light in use in the experiment directly from observation in the interferometer of the changes in the image, caused by interference. An accuracy of up to 1/50 of a wavelength-about 1/100,000 of a millimetre-can be achieved by this method. If we now remind ourselves that the quantities the measurement of which has been made possible by this increase in accuracy - that is, small distances and angles - are precisely those which it is most often necessary to determine in research in precision physics, then without further ado it becomes obvious how powerful an aid has been presented to the physicist in Michelson's interferometer - an invaluable aid, not only because of its efficiency, but also because of the multiplicity of its uses. To illustrate this latter point, it is enough to mention such achievements as, for example, measuring the heat expansion of solid bodies, investigating their elastic behaviour under stress and rotation, determining the margin of error of a micrometric screw, measuring the thickness of thin laminae of transparent solids or liquids, and obtaining the gravitational constant, mass, and average density of the Earth, using both ordinary and torsion balances. Among the more recent uses of the interferometer, by means of which small angle deviations can be recorded with an accuracy of minute fractions of a second, may be mentioned Wadsworth's galvanometric construction, with which can be measured electric currents of vanishingly small intensities with a hitherto unknown degree of accuracy. However, although these uses of the interferometer are important and interesting, nevertheless they are of relatively minor significance in comparison with the fundamental research done by Professor Michelson in the fields of metrology and spectroscopy with the help of these instruments and which, in view of its far-reaching significance for the whole of precision physics, surely deserves in itself to have been recognized with a Nobel Prize. In fact, metrology is concerned with nothing less than finding a method of being able to control the constancy of the intemational prototype metre, the basis of the whole metric system, so accurately that not only will every change, however small, which could possibly occur in it be accurately measured, but also if the prototype were entirely lost, it could nevertheless be reproduced so exactly that no microscope could ever reveal any divergence from the original prototype. The significance of this does not need any particular emphasis, but an outline, however brief, of the course of this research and its results would not be out of place here.

I have already laid emphasis above on the facts that with the help of the interferometer measurements of small length can be made with an extraordinarily high degree of accuracy, and that they may be expressed using the wavelengths of any one type of light as a unit. Moreover, it is possible to measure in this way lengths up to 0.1 metre or more, in suitable conditions, without impairing the accuracy. Thus Michelson's research has first of all prepared the way for the measurement of the value of a standard length of 10 cm in wavelengths of a particular radiation in the cadmium spectrum. Proceeding from the value obtained in this way for the standard 10 cm, with a probable error of at the most ± 0.00004 mm, Michelson was able, likewise using the interferometer, to ascertain on that basis the length of the normal metre, ten times greater, and he obtained for this length a value of

1,553,164.03

wavelengths of this kind to the metre. The probable error in this measurement can in the least favourable conditions amount to only ± 0.0004 mm - that is, less than one wavelength - a value which is far too small to be detected directly by the microscope. Subsequently measurements were carried out in the International Bureau of Weights and Measures in Paris by different observers following an entirely different method, which showed that the error was in fact considerably smaller. These measurements actually give as a value for the length of the metre

1,553,164.13

wavelengths of this kind - a result which differs from Michelson's figure by only 0.1 wavelength, or 0.00006 mm. It is clear from this that Michelson's measurement of the length of the prototype metre must be accurate to within at least 0.0001 mm, and further, that this length can, by the use of his methods, be verified, or in the case of the loss of the prototype be reproduced, with the same degree of accuracy on every occasion. Finally, it also emerges from this that during the interval of 15 years which elapsed between the two series of measurements under discussion, no variation whatsoever from this figure had taken place in the prototype. The great care which had been taken in the execution and preservation of the prototype gave it at least the appearance of a high degree of constancy, but no more; it was only possible to obtain a real proof of its constancy when the metre could be compared with an absolute measure of length, independent of any physical element giving rise to it, the constancy of which under certain given conditions appeared to be guaranteed beyond a shadow of doubt. As far as our present knowledge goes, this is the case with wavelengths of light. It is to Michelson's eternal honour that by his classical research he has been the first to provide such proof.

From the value obtained in this way for the metre in wavelengths of one particular light radiation, it is now also possible to obtain, *vice versa*, figures for these wavelengths on an absolute scale of measurement, with a corresponding degree of accuracy. This accuracy is exceptionally high, and is in fact about fifty times greater than anything obtained by absolute methods in use up till now to determine wavelength. The conviction which had steadily been gaining ground for a long time past, that Rowland's wavelength system, otherwise quite accurate, which has been in use for the last twenty years as the exclusive basis of all spectroscopic research, is with respect to their absolute values subject to quite considerable errors, has thus received full confirmation; it has thus become apparent that a thoroughgoing reassessment of these values is necessary, using either Michelson's or some other similar interference method. And so we have reached the field of spectroscopy, in which it is clear that Michelson's interferometer is capable of an application no less significant than those which we have already considered. This is, however, not its only use. Considering the almost perfect clarity with which the majority of spectral lines appear in the emission spectra produced with the powerful diffraction-grating spectroscopes of our day, there were good grounds for regarding these radiated lines as simple and indivisible things; this is, however, not the case. Making use of his interferometer Michelson has in fact proved that they are, on the contrary, for the most part more or less complex groups of extremely closely packed lines, for the resolution of which the resolving power of even the strongest spectroscope proved utterly inadequate. The discovery of this internal structure of spectral lines to the more thorough investigation of which Michelson later contributed, in the form of the echelon grating invented by him, an even finer means of research than the interferometer, definitely belongs among the most important advances which the history of spectroscopy has ever been able to record, the more so as the nature and condition of the molecular structure of luminous bodies is extremely closely bound up with this structure of spectral lines. Here we are on the threshold of entirely new fields of research, over the unexplored expanses of which Michelson's experiments enable us to cast our first gaze, and his experiments can at the same time serve as a lead to those who are capable of carrying his work a stage further.

In addition to the more or less complicated structure which owing to the peculiar internal nature of luminous bodies is found in spectral lines, it is also possible to split them under the influence of a magnetic force into several more or less closely packed components. A few years ago this Academy was in a position to reward with the Nobel Prize the first exhaustive research, carried out by Professor Zeeman, into this phenomenon, which is extremely important to the science of physics. By using a powerful spectroscope, it is of course possible to examine this phenomenon in its general aspects; as a rule, however, the details are so subtle and so difficult to make out that the resolving power of that instrument is just not adequate for a full investigation. In this case the interferometer - or still better the echelon grating - may be used to advantage, as Michelson has shown. There can remain no shadow of doubt that through this instrument it will be possible to facilitate substantially research into the Zeeman effect.

I have only been able to give here a brief account of the numerous important problems whose solution has been brought so much nearer by the powerful aid to research, with its unprecedented degree of accuracy, which we have received in Michelson's optical precision instruments. This account would certainly seem incomplete if no mention were made of those applications which these instruments have already found, and will surely go on finding, in the field of astronomy, which are almost as important as those in the field of physics. Among these belong the series of measurements of the diameters of the satellites of Jupiter, which have been carried out partly by Michelson himself in the Lick observatory, and partly with the interferometer by Hamy in Paris - a series within which there is substantially closer agreement than it has been possible to achieve with normal micrometric observations through the biggestrefracting telescopes of the present day. Similarly, there can be no doubt whatsoever that it will be possible to obtain considerably more reliable figures in measuring the small planets between Mars and Jupiter than those which have been obtained by the photometric method of observation, which up till now has been the only one available, but which is extremely unreliable. The interferometer method can likewise be of some importance in the investigation of close double and multiple stars, and in this way we may cease to regard as utterly hopeless the problem, which has long been abandoned as completely insoluble, of finding by measurement true values for the diameters of at least the brighter stars. Thus astronomy has once again received from physics in the interferometer - as earlier in the spectroscope - a new aid to research which seems particularly suited to tackling problems whose solution was formerly impossible, as there were no, or at the most inadequate, instruments available.

The aforegoing will suffice, not only to explain to those who are not themselves closely involved in these problems the comprehensive and fundamental nature of Michelson's research in one of the most difficult fields of precision physics, but also to demonstrate how fully justified is the decision of this Academy to reward it with the Nobel Prize in Physics.

The following words were spoken to Professor A. A. Michelson, by Professor the Count K. A. H. Mörner, President of the Royal Swedish Academy of *Sciences,* dur-*ing a private ceremony in the premises of the Academy.*

Professor Michelson. The Swedish Academy of Sciences has awarded you this year the Nobel Prize in Physics in recognition of the methods which you have discovered for insuring exactness in measurements, and also of the investigations in spectrology which you have carried out in connection therewith.

Your interferometer has rendered it possible to obtain a non-material standard of length, possessed of a degree of accuracy never hitherto attained. By its means we are enabled to ensure that the prototype of the metre has remained unaltered in length, and to restore it with absolute infallibility, supposing it were to get lost.

Your contributions to spectrology embrace methods for the determination of the length of waves in a more exact manner than those hitherto known.

Furthermore, you have discovered the important fact that the lines in the spectra, which had been regarded as perfectly distinct, are really in most cases groups of lines. You have also afforded us the means of closely investigating this phenomenon, both in its spontaneous occurrence and when it is produced by magnetic influence, as in Zeeman's interesting experiments.

Astronomy has also derived great advantage, and will do so yet more in the future, from your method of measurements.

In bestowing the Nobel Prize in Physics upon you the Academy of Sciences desires to signalize as worthy of especial honour the eminently successful researches you have carried out. The results you have attained are excellent in themselves and are calculated to pave the way for the future advancement of science.

ALBERT A. MICHELSON

Recent advances in spectroscopy

Nobel Lecture, December 12,1907

The fame of Newton rests chiefly on his epoch-making discovery of the laws of gravitational astronomy - by means of which the position of the moons, the planets, and the comets, and other members of our solar system can be calculated and verified with the utmost precision - and in many cases such calculation and verification may be extended to systems of suns and planets outside our own.

But in no less degree are we indebted to this monumental genius for that equally important branch of Astrophysics - in which the spectroscope plays so fundamental a role - by means of which we are enabled to discover the physical and chemical constitution of the heavenly bodies, as well as their positions and motions. As the number and intricacy of the wonderful systems of stellar worlds which the telescope can reveal increase with its power, so also do the evidences of the innermost molecular structure of matter increase with the power of the spectroscope. If Newton's fundamental experiment of separating the colors of sunlight had been made under conditions so slightly different from those in his actual experiment that in the present stage of experimental science, they would at once suggest themselves to the veriest tyro - the science of spectroscopy would have been founded.

So simple a matter as the narrowing of the aperture through which the sunlight streamed before it fell upon the prism which separates it into its constituent colors - would have sufficed to show that the spectrum was crossed by dark lines, named after their discoverer, the Fraunhofer lines of the Solar Spectrum. These may be readily enough observed, with no other appliances than a slit in a shutter which is observed through an ordinary prism of glass. Fraunhofer increased the power of the combination enormously by observing with a telescope - and this simple combination, omitting minor details, constitutes that wonder of modern science, the Spectroscope. As the power of a telescope is measured by the closeness of the double stars which it can <<resolve>>, so that of the Spectroscope may be estimated by the closeness of the spectral lines which it can separate. In order to form an idea of the advance in the power of spectroscopes let us for a moment consider the map of the Solar Spectrum (Figure 1).

The portion which is visible to the unaided eye extends from the Fraunhofer line A to H; but by photography it may be traced far into the ultra-violet region and by bolometric measurements it is found to extend enormously farther in the region beyond the red. In the yellow we observe a dark line marked *D*, which coincides in position with the bright light emitted by sodium - as when salt is placed in an alcohol flame. It may be readily shown by a prism of very moderate power that this line is double, and as the power of the instrument increases the distance apart or separation of this doublet furnishes a very convenient measure of its separating or resolving power. Of course this separation may be effected by simple magnification, but this would in itself be of no service, as the <<lines>> themselves would be broadened by the magnification in the same proportion. It can be shown that the effective resolving power depends on the material of the prism which must be as highly dispersive as possible and on the size, or number, of the prisms employed - and by increasing these it has been found possible to <<resolve>> double lines thirty or forty times as near together as are the sodium lines. It will be convenient to take the measure of the resolving power when just sufficient to separate the sodium lines as 1,000. Then the limit of resolving power of prism spectroscopes may be said not much to exceed 40,000.*

This value of resolving power is found in practice to obtain under average conditions. Theoretically there is no limit save that imposed by the optical conditions to be fulfilled - and especially by the difficulty in obtaining large masses of the refracting material of sufficient homogeneity and high dispersive power. It is very likely that this limit has not yet been reached.

Meanwhile another device for analysing light into its component parts has been found by Fraunhofer (1821) which at present has practically superseded the prism-namely, the diffraction grating. Fraunhofer's original grating consisted of a number of fine equidistant wires, but he afterwards made them by ruling fine lines on a glass plate covered with gold leaf and removing the alternate strips. They are now made by ruling upon a glass or a metal surface fine equidistant lines with a diamond point.

The separation of light into its elements by a grating depends on its action on the constituent light-waves.

Let Fig. 2 represent a highly magnified cross section of a diffraction grating with plane waves of light falling upon it normally, as indicated by the ar-

* Lord Rayleigh has obtained results with prism of carbon disulphide which promise a much higher resolving power.

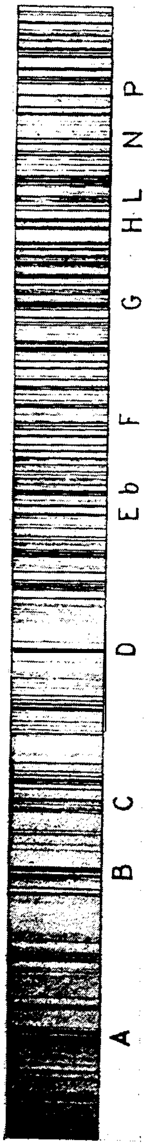

Fig.1.

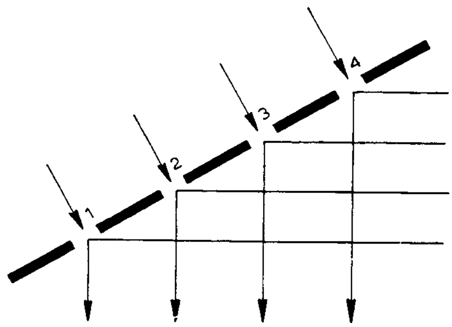

Fig.2.

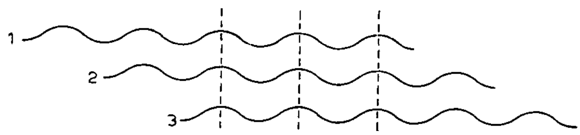

Fig. 3.

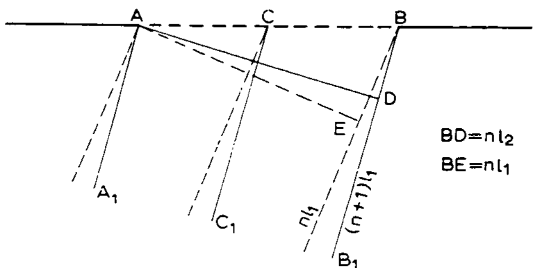

Fig. 4.

rows. The wave motion will pass through the apertures, and will continue as a series of plane waves; and if brought to a focus by a telescope will produce an image of the slit source just as if no grating were present (save that it is fainter, as some of the light is cut off by the opaque portions). This image may be considered as produced by the concurrence of all the elementary waves from the separate apertures meeting in the same phase of vibration, thus re-inforcing each other. But this may also be true in an oblique direction, as shown in the figure, if the retardation of the successive waves is just one whole wavelength (or any whole number) as is illustrated in Fig. *3*, where the successive waves from apertures 1, 2, 3 ... are shown to re-inforce each other just as if they all belong to a single wave-train. In this direction therefore there will also be an image of the slit source; and this direction is determined by the relation:

$$\sin\theta = \frac{m\,l}{s}$$

where *l* is the length of the light-wave of this particular color, s the distance between the apertures (the grating space), and *m* the number of waves in the common retardation (1,2,3, etc.). But even if the light thus diffracted be absolutely homogeneous (that is, consist of an infinite wave-tram of constant wavelength) it does not follow that the light is all diffracted in the given direction; there will be some light in directions differing slightly from this - growing less until the extreme difference of path is (say) n + I waves, (instead of n when it is ml).

In fact, if we divide the pencil having this new direction into two equal parts *AC* and *CB*, the ray *AA*, will be $n + 1/2$ waves in advance of CC_I and the two will be in opposite phases of vibration, and will therefore neutralize each other. The same will be true of each pair of rays taken in the same manner over the whole grating space, and the result is total darkness for this direction. Let us suppose we are examining the double sodium line. The difference between the components is about one thousandth of the wave-length. With a grating of *n* lines there will be total darkness in a direction corresponding to a retardation of (n + I) l. Let this direction correspond to the brightest part of the image for the second sodium line 1_2 so that (n + I) $l = n\,1_2$ or $(1_2 - 1_1)/s = l/n$. Under these conditions the two images are just <<resolved>>. But $(1_2 - 1_1)/l = l/1{,}000$ for sodium lines, whence n = 1,000. That is, a grating of 1,000 lines will <<resolve>> the sodium lines in the first spectrum, or R = 1,000. In the second (where the common retardation is two wavelengths) the resolving power is twice as great or $2n$, and in the m*th* spectrum, m times as great. The resolving power is therefore the product of the number of lines in the grating by the order of the spectrum, that is, $R = mn$.

In order, therefore, to obtain high resolving power the grating must have a great number of rulings and if possible a high order of spectrum should be used. The rulings need not be exceedingly close together, but it is found practically sufficient if there are from 500 to 1,000 lines per millimeter. The earlier gratings were relatively small and contained only a few thousand lines. The best of these were ruled by Nobert (1851). A very great advance was made by Rutherford of New York, who (1868) ruled gratings two inches long on speculum metal and containing about 20,000 lines. These gratings exceeded in resolving power the best prism trains in use at the time. The next advance was made by Rowland of the Johns Hopkins University, who succeeded in ruling gratings six inches long (by two to three inches stroke) having about one hundred thousand lines, and capable (theoretically, at least) of resolving in the spectrum, double lines whose distance apart was only one one-hundredth as great as that of the sodium lines. Practically this is about the limit of the power of the best Rowland grating which I have examined.

The difference between the theoretical and the actual performance is due to want of absolute uniformity in the grating space. This is due to the enormous difficulty in constructing a screw which shall be practically perfect throughout its whole length, a difficulty which increases very rapidly as the length of the screw increases; and it has been supposed that the limit of accuracy was reached in these gratings.

The great and rapidly increasing importance of spectrum analysis - especially in determining the distribution of light in so-called spectral lines under normal conditions, the resolution of complicated systems of lines, and in the investigation of the effects of temperature, of pressure, and especially of a magnetic field -justified the untertaking of much larger gratings than these. As an example of progress made in this direction, I have the honor of exhibiting a grating having a ruled surface nine inches long by four and one half inches stroke (220 x 110mm). This has one hundred and ten thousand lines and is nearly perfect in the second order; so that its resolving power is theoretically 220,000 and this is very nearly realized in actual experiments.

It will be observed that the effect produced at the focus of the telescope depends on the concurrence or opposition - in general on the *interference of* the elementary trains of light-waves. We are again indebted to the genius of Newton for the first observation of such interference; and a comparatively slight modification of the celebrated experiment of <<Newton’s rings>> leads to a third method of spectrum analysis which, if more indirect and less convenient than the methods just described, is far more powerful. If two plane surfaces (say the inner surfaces of two glass plates) are adjusted very accurately to parallelism, and sodium light fall on the combination at nearly normal incidence, the light reflected from the two surfaces will interfere, showing a series of concentric rings alternately bright and dark, according to the relative retardation of the two reflected light beams.

If this retardation changes (by slowly increasing the distance between the surfaces) the center of the ring system goes through alternations of light and darkness, the number of these alternations corresponding exactly to the number of light-waves in twice the increase in distance. Hence the measurement of the length of the waves of any monochromatic light may be obtained by counting the number of such alternations in a given distance. Such measurement of wavelengths constitutes one of the most important objects of spectroscopic research.

Another object accomplished by such measurement is the establishment of a natural standard of length in place of the arbitrary standard at present in use - the meter. Originally it was intended this should be the ten-millionth part of an earth-quadrant, but it was found that the results of measurements differed so much that this definition was abandoned. The proposition to make the ultimate standard the length of a pendulum which vibrates seconds at Paris met with a similar fate.

Shortly after the excellent gratings made by Rutherford appeared, it was proposed (by Dr. B. A. Gould) to make the length of a wave of sodiumlight the ultimate standard; but this idea was never carried out. It can be shown that it also is not susceptible of the requisite degree of accuracy, and in fact a number of measurements made with a Rowland grating have been shown to be in error by about one part in thirty thousand. But modern conditions require a much higher degree of accuracy. In fact, it is doubtful if any natural standard could replace the arbitrary standard meter, unless it can be shown that it admits of realization in the shape of a material standard which can not be distinguished from the original.

One of the most serious difficulties encountered in the attempt to carry into practice the method of counting the alternations of light and darkness in the interference method, is the defect in homogeneity of the light employed. This causes indistinctness of the interference rings when the distance is greater than a few centimeters. The light emitted by various kinds of gases and metallic vapors, when made luminous by the electric discharge, differ enormously in this respect. A systematic search showed that among some forty or more radiations nearly all were defective, some being represented by a spectrum of broad hazy «lines», others being double, triple, or even more highly complex. But the red light emitted by luminous vapor of metallic cadmium was found to be almost ideally adapted for the purpose. Accordingly this was employed : and the results of three independent measurements, made by different observers and at different times, of the number of light-waves of red cadmium light in the standard meter are as follows:

I	1,553,392.4
II	1,553,393.2
III	1,553,393.4.

It will be seen that the differences are less than half a millionth part, and this is about the limit of accuracy of the comparative measurements of the material standards. Within the last year a similar determination has been carried out by Perot and Fabry, with a result not to be distinguished from the above. It follows that we now have a natural standard of length, the length of a light-wave of incandescent cadmium vapor; by means of which a material standard can be realized, whose length can not be distinguished from the actual standard meter-so that if, through accident or in time, the actual standard meter should alter, or if it were lost or destroyed, it could be replaced so accurately that the difference could not be observed.

In the search for a radiation sufficiently homogeneous for the purpose of a standard it became evident that the interference method might be made to yield information concerning the distribution of light in an approximately homogeneous source when such observations would be entirely beyond the power of the best spectroscopes. To illustrate, suppose this source to be again the double radiation from sodium vapor. As the wavelengths of these two radiations differ by about one part in a thousand, then at a difference of path of five hundred waves (about 0.36 mm) the bright fringes of one wave-train would cover the dark fringes of the other, so that if the two radiations were of equal intensity, all traces of interference would vanish. At twice this distance they would reappear and so on indefinitely, if the separate radiations were absolutely homogeneous. As this is not the case, however, there would be a gradual falling off in the clearness or visibility of the bands. Inversely, if such changes are observed in actual experiment, we infer that we are dealing with a double source. Further, from the distance between the maxima of distinctness, we may determine (and with extraordinary accuracy) the ratio of wavelenghts of the components; from the ratio of maxima to minima we may infer the ratio of their intensities; and finally the gradual falling off when the distance becomes large gives accurate information of the <<width>> of the corresponding spectral lines.

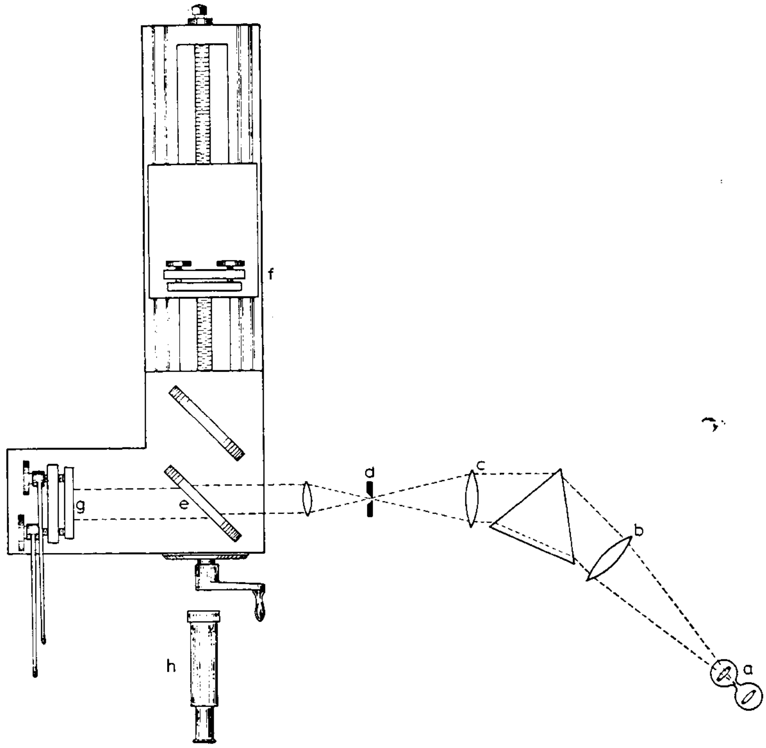

Fig. 5.

In this way it was found that the red line of hydrogen is a double with components about one fortieth of the distance apart of the sodium lines. Thallium has a brilliant green radiation which is also double, the distance being one sixtieth that of the sodium lines. Mercury shows a brilliant green line, which is highly complex, but whose chief component is a doublet, whose separation is only one seven-hundredth of that of sodium. The interference fringes are still visible when the difference of path is of the order of five hundred millimeters, corresponding to over a million light-waves; and the corresponding width of spectral line would be less than a thousandth part of that which separates the sodium lines.

Fig. 5 illustrates the arrangement of the apparatus as it is actually used. An ordinary prism spectroscope gives a preliminary analysis of the light from the source. This is necessary because the spectra of most substances consist of numerous lines. For example, the spectrum of mercury contains two yellow lines, a very brilliant green line, and a less brilliant violet line, so that if we pass all the light together into the interferometer, we have a combination of all four. It is usually better to separate the various radiations before they enter the interferometer. Accordingly, the light from the vacuum tube at *a* passes through an ordinary spectroscope *b c*, and the light from only one of the lines in the spectrum thus formed is allowed to pass through the slit *d* into the interferometer.

As explained above, the light divides at the plate *e*, part going to the mirror *f*, which is movable, and part passing through, to the mirror *g*. The first ray returns on the path *f e h*. The second returns to e, is reflected, and passes into the telescope *h*.

The resolving power of the interferometer is measured by the number of light-waves in the difference of path of the two interfering pencils, and as this is unlimited, the interferometer furnishes the most powerful means for investigating the structure of spectral lines or groups. Its use is, however, somewhat handicapped by the fact that the examination of a single group of lines may require a considerable number of observations which take some time and during which it may be difficult to prevent changes in the light source. Nevertheless it was found possible by its means to investigate the wonderful discovery of Zeeman - of the effect of a magnetic field on the character of the radiation from a source subjected to its influence; and the results thus obtained have been since confirmed by methods which have been subsequently devised.

One of these is the application of the echelon. This is in effect a diffraction grating in which high resolving power is obtained by using a very high order of spectrum into which practically all, the light is concentrated. The number of elements may be quite moderate - since the resolving power is the product of the two. The order of the spectrum is the number of wave-lengths in the retardation at each step. This retardation (which must be very accurately constant) is secured by allowing the incident light to fall upon a pile of glass plates optically plane parallel and of the same thickness - each one a little wider than the preceding as in Fig.6.

Fig.6.

Thus if the pile has forty plates, each one centimeter thick, the retardation will be about ten thousand light-waves; and the resolving power would be forty times this or four hundred thousand - which is about four times as that of a six-inch diffraction grating of the usual form. The number of elements might be increased till the absorption of the glass brought a limit. A difficulty, which appears long before this limit is reached, is due to the loss of light by repeated reflections between the many surfaces. This has been very ingeniously overcome by Mr. Twyman of the firm of Hilger & Company by pressing the plates together to actual contact - when the reflection vanishes. It is likely that the echelon under these conditions may be used by reflection instead of transmission (the plates being silvered for the purpose) with the advantage of quadrupling the resolving power for the same number of plates and eliminating the absorption.

An illustration of the efficiency of the echelon spectroscope is furnished by the following photographs of the spectrum of green radiations from mercury vapor. The first of the figures shows the spectrum of the second order of a diffraction grating whose ruled surface is nine inches by four and a half - the largest in existence. The second is by an echelon of thirty plates, seven millimeters thick, and in the third the echelon consisted of forty plates, each an inch and a fourth thick (30 mm). The corresponding lines are similarly lettered in the three figures. The scale is in Å.U.(Ångstrom units). It will be noted in the last of the three figures that the midth of the fainter companion is about one one-hundredth of an Å.U. The limit of resolution of the instrument is about half as much, or its resolving power is over a million (Figs. 7,8 and 9).

It will be observed that the echelon spectra are repeated - thus a_1 and a_2 are two successive spectra of the same line. This is true of any grating spectrum, and the difficulties which arise from the overlapping of the suc-

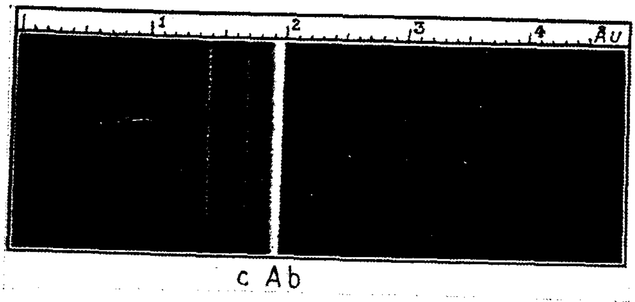

Fig.7.

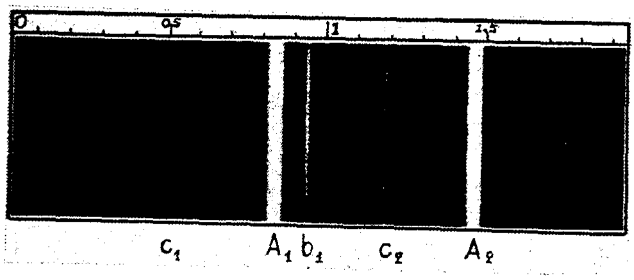

Fig.8.

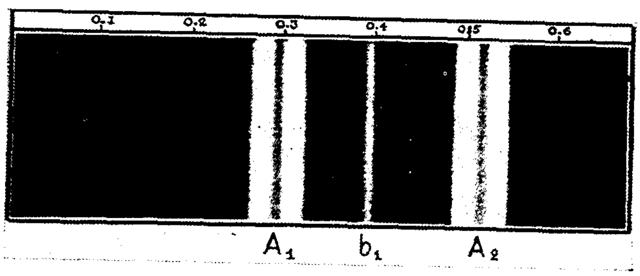

Fig.9.

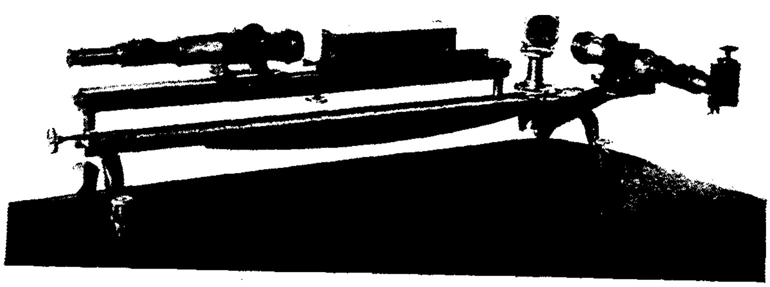

Fig.10.

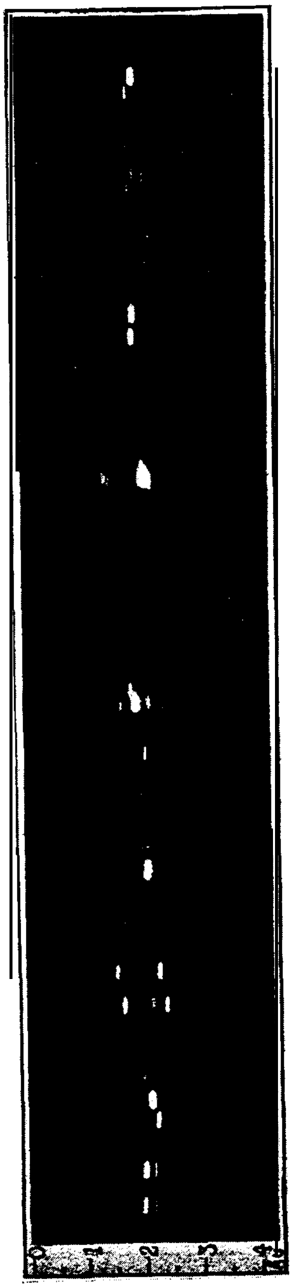

Fig.11.

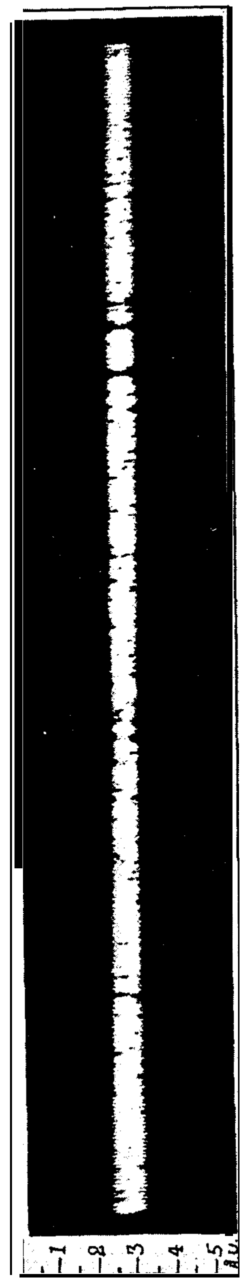

Fig.12.

cessive orders of spectrum may be overcome by separating these by a prism whose refracting edge is perpendicular to the lines of the grating. The same is true of the echelon spectrum - save that the order of the overlapping spectra is so high that a prism is hardly adequate and recourse must be had to a grating - with its plane of diffraction perpendicular to that of the echelon, as shown in Fig. 10.

With this arrangement it is possible to photograph a large part of the spectrum at once.*

Fig. 11 shows such a photograph of the iron spectrum, and it may be noted that this combination of grating and echelon makes it possible to observe absorption spectra as well as bright line spectra.

Fig.12 shows a photograph of the solar spectrum taken in this way. It will be noted that the spectral <<lines>> are generally too broad to justify the use of so great a resolving power.

Finally it may be pointed out that this combination gives us the means of comparing the wavelengths of spectral lines with a degree of accuracy far superior to that of the grating.

* If the preliminary analysis has been made before the light entered the slit of echelon spectroscope, it would be possible to examine but one-at most a few -lines at a time.

Biography

Albert Abraham Michelson was born in Strelno, Prussia, on December 19, 1852. Two years later his family emigrated to the United States to settle at Virginia City, Nevada, but they eventually moved to San Francisco where Michelson received his early education in public schools, matriculating from the High School in 1809. He was appointed by President Grant to the U.S. Naval Academy and, after graduation as Ensign in 1873 and a two-years' cruise in the West Indies, he became an instructor in physics and chemistry at the Academy under Admiral Sampson. In 1879, he was posted to the Nautical Almanac Office, Washington, to work with Simon Newcomb, but in the following year, he obtained leave of absence to continue his studies in Europe. He visited the Universities of Berlin and Heidelberg, and the College de France and École Polytechnique in Paris. He resigned from the Navy and in 1883 returned to America to take an appointment as Professor of Physics in the Case School of Applied Science, Cleveland, Ohio. In 1890 he accepted a similar position at Clark University, Worcester, Massachusetts, and in 1892 he became Professor of Physics and the first Head of Department at the new University of Chicago. He rejoined the Navy during World War I, and in 1918 returned to Chicago where in 1925 he was appointed to the first of the Distinguished Service Professorships. Michelson resigned in 1929 to work at the Mount Wilson Observatory, Pasadema.

During his career, Michelson touched on many departments of physics but, perhaps due to a special instinct which he appeared to possess, he excelled in optics. He performed early measurements of the velocity of light with amazing delicacy and in 1881 he invented his interferometer for the purpose of discovering the effect of the Earth's motion on the observed velocity. In cooperation with Professor E. W. Morley, and using the interferometer, it was shown that light travels at a constant speed in all internal systems of reference. The instrument also enabled distances to be measured with greater accuracy by means of the length of light-waves. At the request of the International Committee of Weights and Measures, Michelson measured the standard metre in terms of wavelength of cadmium light. He invented the echelon spectroscope and during his wartime service in the Navy he performed research work on devices for naval use - he developed a range-finder which was adapted as part of U.S. Navy equipment. On his return to civilian life, Michelson became more interested in astronomy and in 1920, using light interference and a highly developed version of his earlier instrument, he measured the diameter of the star Betelgeuse: this was the first determination of the size of a star that could be regarded as accurate.

Michelson has contributed numerous papers to many scientific periodicals and among his more substantial works are the classics, Velocity & Light (1902) *Light Waves and their Uses* (1899-1903); and *Studies in Optics* (1927).

Michelson was honoured by memberships of many learned societies throughout America and ten European countries, and he received honorary science and law degrees from ten American and foreign universities. He was President of the American Physical Society (1900), the American Association for the Advancement of Science (1910--1911), and the National Academy of Sciences (1923-1927). He was also a Fellow of the Royal Astronomical Society, the Royal Society of London and the Optical Society, an Associate of l'Académie Française and among the many awards he has received are the Matteucci Medal (Societá Italiana), 1904; Copley Medal (Royal Society), 1907; Elliot Cresson Medal (Franklin Institute), 1912; Draper Medal (National Academy of Sciences), 1916; Franklin Medal (Franklin Institute) and the Medal of the Royal Astronomical Society, 1923; and the Duddell Medal (Physical Society), 1929.

Michelson married Edna Stanton of Lake Forest, Illinois in 1899. They had one son and three daughters. He died in 1941.