inside the atoms. And it has now been found possible to predict what particular orbit a loosed electron will fall into. This is possible because when an electron shifts from an outer orbit to one nearer the nucleus it sends out a flash of light of a definite color, that is to say the waves of the emitted light are of a certain length and a corresponding frequency. The "frequency" means the number of waves passing a given point in a second. The longer the waves. of course, the less the frequency. The frequency and wave length of the light radiated by any star or incandescent gas can be determined by the location of the bright lines in its spectrum.

Prof. R.A. Millikan of the California Institute of Technology has recently discovered a way of stripping off one by one the outer electrons from an atom and he can tell in advance with amazing accuracy just what sort of light will be emitted by such a stripped atom. Last year Dr. Millikan was awarded the Nobel Prize in physics for the ingenious piece of apparatus that enabled him to catch and count the loose electrons and calculate their electric charge. He has this year penetrated still further into the mystery of atomic structure. His new discovery was to have been explained to the National Academy of Sciences on the afternoon of April 29, but on account of the tragic death of Dr. E.F. Nichols while addressing the Academy that morning no further papers were read during the day. But Professor Millikan has kindly consented to give Science Service a plain account of what he has done and what it means.

THE ASTRONOMY OF THE ATOM

By Dr. Robert A. Millikan,
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The world is just entering upon a period of development of atomic mechanics, or of the astronomy of the atom, which has many points in common with the period of development of celestial mechanics which occupied the two or two and a half centuries following Galileo. Celestial mechanics was made possible through the invention of the telescope. The spectroscope bears precisely an analogous position with respect to atomic mechanics. The telescope made it possible to determine the exact orbits of heavenly bodies and to check by precise observation of such phenomena as the time of eclipses the theoretical results which are consequences of the Newtonian laws. Similarly, today the spectroscope has furnished the physicists with means for the quantitative testing of the recently developed laws of atomic mechanics, and it is today furnishing as exacting proof of the orbital theory of electronic motions as the telescope furnished a century earlier for the orbital theory of the motions of heavenly bodies.

The present paper shows not merely what kind of phenomena can be predicted with the aid of the orbital theory of electrons and atoms, but with what amazing precision these predictions are verified by the test of experiments. These results have been made possible because of the development of high vacuum "hot spark" spectrometry with the aid of which we were able first in 1920 to push three or four octaves farther into the ultra-violet than preceding investigators had gone. For the sake of simplicity, I shall at first confine attention to the radiations emitted by one particular atom, namely, the atom of boron, familiar to every household because of the abundant use of boracic acid for disinfecting purposes.

The atom of boron is the fifth in the order of increasing atomic weights, hydrogen being the lightest, helium the next, lithium the next, beryllium the next, and boron the next. This means that the nucleus of the boron atom contains five free positive electrons and that five negative electrons are held outside the nucleus, or just enough to make the normal boron atom electrically neutral. Of these five electrons, two have been proved heretofore, and are again proved in this paper, to be close to the nucleus. The remaining three are four or five times more remote from the nucleus and are called its valence electrons. For the sake of later comparison it is useful to recall that lithium possesses one of these valence electrons, beryllium, two, boron three, carbon four, nitrogen five, oxygen six, and fluorin seven, which is the highest number possessed by any known atom having the possibility of combining with other atoms at all.

Now the interesting property of our hot sparks, which are very high potential discharges in the highest vacua between electrodes from a fraction of a millimeter up to one or two millimeters apart, is that such hot sparks possess an extraordinary ionizing power. Mr. I.S. Bowen and myself at the California Institute of Technology have recently definitely proved that these hot sparks have the power of stripping a great many atoms completely of all their valence or outer electrons. These stripped atoms of lithium, beryllium, boron, carbon, and nitrogen, for example, are then completely similar atomic structures, save for the fact that the central charge increases in the ratios one, two, three, four, five in going from lithium to nitrogen. This is the first time that it has become possible to compare the radiating properties of such a long series of similar atomic structures and the discovery of a means of obtaining such a series has furnished the opportunity of getting some very interesting checks upon the theory of electronic orbits.

Now the theory of electronic orbits in atoms is similar to the theory of planetary orbits in astronomy save that the atoms have one restriction unknown to the former, While celestial mechanics permits of the existence of as many orbits as you please around a given central sun, atomic mechanics permits of a very limited number of orbits whose radii progress (in the simple Bohr theory) in the ratio of the squares of the numbers one, two, three, four, five, etc. Atomic mechanics also differs from celestial mechanics in the mechanism by which the existence of a particular orbit can be experimentally tested. Thus, the most exact test which astronomy offers for the correctness of hypothetical planetary orbits is the prediction of the instant of passage of two such orbits through a given line so as to produce an eclipse. If the eclipse occurs at the predicted instant, it is considered that the theory which made the predictions possible has received extraordinary quantitative support. In the astronomy of the atom, on the other hand, we cannot observe an eclipse, but what we do observe is the frequency (the reciprocal of the wave-length) of the radiation emitted when an electron jumps from one of its possible orbits to another. These jumps always occur from the orbits more remote from the nucleus to those which are closer to it and the difference in the energies of the electrons in the two orbits (which I shall call the energy of the orbit itself) is found to be in every case exactly proportional to the frequency emitted. It is this frequency which the spectroscope immediately brings to light as a spectral line whose wave length, and therefore whose frequency, it enables us very accurately to measure.

The whole number of different orbits which are possible in such a simple nucleus-electron-system as is furnished by the hydrogen atom has long been accurately known experimentally, and these known orbits have been fitted beautifully and accurately into what is known as the simple Bohr theory.

This theory requires that if the charge on the nucleus should be successively given the values one, two, three, four, five, the frequencies of all of the orbits would be increased in the ratios one, four,nine, sixteen, twenty-five. Now thediscovery of the possibility of stripping all the valence electrons off the atoms of lithium, beryllium, boron, carbon, and nitrogen has given us the means of comparing the radiations from what are in effect simple nucleus-electron-systems in which the charge on the nucleus increases in the ratios one, two, three, four, five, provided always that we are comparing orbits in different atoms which are so remote from the nucleus that the pair of electrons which, as indicated above, is near the nucleus in all the atoms may be considered as exerting their forces as though they were in the nucleus itself.

To return now to the consideration of the stripped boron atom. When Mr. Bowen and I began to get evidence that our hot sparks were stripping the boron atoms of all their valence electrons we set to work to predict exactly what sort of frequencies (or of wave lengths) we might expect to be emitted by the stripped boron atoms as a single electron, in being drawn into this stripped atom, began to jump between the possible orbits which ought to exist about it. Thus, on the basis of our knowledge of the spectral lines emitted by hydrogen, we predicted at once that an electron in jumping from the fifth to the fourth of these possible orbits would produce a line of just nine times the frequency of the radiation produced when the hydrogen atom electron jumped from the fifth to the fourth orbit. We computed in this way that this stripped boron atom ought to have a line whose wave length was 4500 Angstrom units, that is, a line in the blue region of the ordinary visible spectrum. No such line had ever been observed with boron thus far, but no one had before worked with light like that given off by our hot sparks which one could expect would produce stripped boron atoms. So we made our exposure, developed our plate, and found our predicted line which no one had ever seen before at exactly the wave length 4499.0, or within one part in 5000 of the predicted spot. In other words, our predicted "eclipse" in the field of astronomical orbits had occurred at exactly the right time.

We also computed the radiation that would be produced when the electron circuling around the stripped boron atomsfell from the third orbit to the second and got 678 angstroms. We looked up our table of boron lines in the extreme ultra-violet which we had published last January and found that we had recorded a strong line at wave length 677 angstroms, but if this were indeed due to the stripped boron atom it ought to be, like the so-called D line of sodium, a doublet, that is, a pair of lines very close together. It had not appeared so on our old plate, but the spectrograph had not been one which could have separated this pair, even if it existed, so we built a new spectrograph of higher resolving power and took another photograph of this line and found that it was indeed a doublet just as our orbit theory demanded, the two components of which had wave lengths of 677.01 and 677.16.

We have now brought to light all of the lines which were to be expected from the stripped boron atom and by checking all of these predictions by experiment we had proved with absolute certainly that in our hot sparks we were producing stripped boron atoms.

But someone says: Are these resutlts dependent upon your orbit theory ofthe motion of electrons? Thus far, not completely, but in the next stage they are completely so dependent. I have spoken of the doublets which we found produced by the stripped boron atom. Now the principal lines in the spectrum of hydrogen are also doublets and a beautiful theory was developed by Professor Sommerfeld for explaining these doublets. He showed that there ought to be two orbits, one circular and one elliptical, which would have exactly the same energy if it were not for the fact that the mass of the electrons in the elliptical orbit should grow greater as its speed increased in going through perihelion and smaller as it went through aphelion, and that because of the dependence of mass upon speed which is required by the Einstein theory of relativity. He further computed exactly with the aid of that theory the differences in the energies of two orbits, the one circular and the other elliptical, and found that this theory, which yielded a formula in which there were no undetermined constants at all, predicted completely and exactly the observed frequency separation of the hydrogen doublet. We now tried this relativity doublet theory upon the doublets which we had found in lithium, beryllium, boron, and carbon, and found that this purely theoretical formula predicted exactly the observed separations in all cases. We then predicted from this formula the separation of the doublet which ought to be produced by the stripped nitrogen atom and looking in the nitrogen spectrum found a nitrogen doublet with precisely the correct separation and at a wave length which we could also predict by our theory. We had thus brought to light a most powerful instrument with which we can now alanyze the light that comes from any kind of a source, for example, a very hot star, and know at once by comparison with the theory of observed lines whether stripped atoms of a whole series of substances exist or do not exist in the sources. In this way, we have definitely proved the existence in our hot sparks of stripped atoms of lithium, silicon, phosphorus, and sulphur, this last atom having been stripped of six valence electrons, phosphorus of five, silicon of four, aluminum of three, magnesium of two, and sodium of one.

These methods bring to light new ways of going on eclipse expeditions in the study of the astronomy of the sub-atomic world and they reveal new possibilities for the reading of the conditions existing in the stars. Truly, we are just now entering upon a period of the fascinating study of the astronomy of the atom, a period in which the spectroscope is the instrument with which we must bring to light wonders no less fascinating than those which the telescope has revealed in the study of the stars.

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ASTRONOMERS DEBATE EINSTEIN'S SHIFT OF SOLAR SPECTRUM

Einstein's third prediction, that the spectrum of the sun is shifted slightly toward the red end as compared with light from the earth, is not borne out by experimental evidence presented to the National Academy of Sciences at its annual session at Washington, by Dr. Heber D. Curtis, director of the Allegheny Observatory, Pittsburg.