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A New Method for Studying the Atom

Optical spectra for multiply ionized atoms are produced by means of nuclear-physics techniques.

Stanley Bashkin

Traditional atomic spectroscopy has left two major problems essentially unsolved. Consider an atom which normally contains Z electrons. It is clear that the loss of an electron—that is, ionization of the atom—means that the energy levels for the remaining $(Z - 1)$ electrons will differ from those which exist when the atom is electrically neutral. These levels can be determined from the spectrum of the ion. Similarly, two, three, or more electrons can be removed, until but one remains, a new spectrum, corresponding to a new set of energy levels, appearing for each of the stages of ionization. One of the major outstanding problems is to produce the spectra of multiply ionized atoms.

Why is this hard? It's hard because it takes a lot of energy to remove several electrons from a single atom. In principle, such deductions can be made just by heating. In practice, the required temperatures may be millions of degrees Celsius, so that such an approach is impractical. True enough, some of the present thermonuclear machines do create temperatures in excess of 10^6 deg K, and excellent spectroscopy is carried out with these machines, but the difficulties are formidable. For one, it is virtually impossible to avoid contaminants, and the physical conditions are so unfamiliar that identification of the source atom for an observed line is not always unambiguous. Second, at any given temperature and pressure, the atoms are not all ionized to the same extent. Rather, there is some ionization distribution, and there is often a question as to which stage of ionization fathers a particular spectral line. Third, the thermal motion of the atoms and ions broadens the spectral lines and hence obscures their true origin. Finally, it is frequently important to know how many emitting atoms are present in the source, and this, too, is hard to establish for the hot plasmas.

The other prominent problem is even tougher and has been solved but rarely even for neutral atoms, let alone highly charged ions. A feature of the excited levels is that an electron cannot stay in one of them forever. In fact, it is well established that the average time an electron can stay in an excited state is around 10^{-8} sec, although a factor of 10^4 either longer or shorter may also occur. Despite this general knowledge, the specific measurement of atomic lifetimes has been one of the most refractory of all problems. In one method now being used with some success, a short burst of electrons enters a gas and excites the atoms by collision. As the excited atoms resume their quiescent configuration they emit light, and the decay of light intensity with time yields the desired average lifetime. However, this technique is limited to measurement of the lifetimes in neutral atoms of noble gases. Other methods suffer from similar limitations and experimental complications.

The author is professor of physics at the University of Arizona, Tucson.

Three Needs

In the past decade there has been revived interest in the spectra of multiply ionized atoms and the lifetimes of atomic energy levels. Let me cite three different needs for this information.

As I have mentioned, man-made temperatures of 10^6 deg K or more are generated in attempts to initiate a controlled fusion of nuclei. The temperature is one of the most important physical factors in thermonuclear devices. Clearly the thermometer which can measure such temperatures is a bit out of the ordinary. The fact that numerous electrons are torn away from their parent atoms at 10^6 deg K means that any spectra evolved are characteristic of highly ionized particles. Now, the extent of the ionization and the nature of the spectra are functions of the temperature, so one can use the observed spectra to deduce the temperature—in principle. In practice, this is like putting the cart before the horse, because the spectra cannot be used reliably until one knows what kind of light the electron-deficient atoms emit. In the absence of reliable spectral data, the temperature determinations may be uncertain. Difficult theoretical calculations are now used to make the spectral assignments.

The second need arises from recent studies of the sun. It appears that the temperature of the solar corona is around 10^6 deg K. This conclusion has been reached because the spectra—especially those obtained with rocket-borne equipment which, from above most of the earth's atmosphere, detects

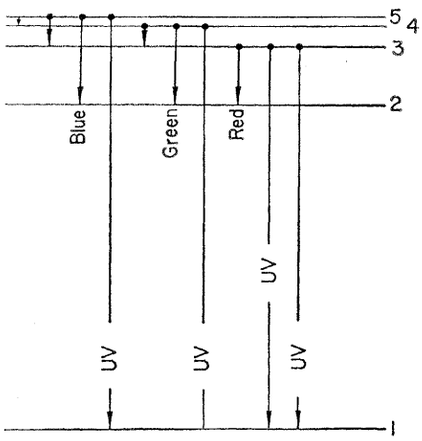

Fig. 1. Some of the energy levels and competing electronic transitions in hydrogen. The length of an arrow is a measure of the energy released as light when the electron moves between the initial and the final states. *UV*, ultraviolet.

lines in the extreme ultraviolet—appear to be due largely to multiply ionized atoms. Thirteen-times-ionized iron, for example, is believed to be prominent in the solar corona. However, about 25 percent of the coronal lines are yet to be identified, and, again, the paucity of good laboratory data makes for uncertainty in assigning the sources of some of the other 75 percent.

Finally, there is the fascinating problem of finding the relative abundances of the elements in the sun and other stars. This information forms the basis for theories of stellar-energy production, of the origin of the chemical elements, and of the age and evolution of stars. Suppose a stellar spectrum contains the red light of hydrogen. How can one tell from the intensity of this light how many hydrogen atoms are present? Two basic factors enter into the answer. The first is the condition of the stellar atmosphere, since this may or may not be suitable for exciting the hydrogen atoms to the levels from which the red light comes. The second factor is the oscillator strength—the fraction of the hydrogen atoms which, on being excited to the correct levels, will emit red light in preference to light of other colors which can come from the same levels. A few of the possibilities, simple for the case of hydrogen, are illustrated in Fig. 1.

The first factor—the condition of the stellar atmosphere—is determined by the astrophysicists on the basis of an overall study of the star's behavior. The second—the oscillator strength—is fixed by the detailed structure of the hydrogen atom, and one can show that the lifetime of an excited level is an excellent guide for determining oscillator strengths for the different kinds of light which can come from that level.

Method of Measurement

It occurred to me a few years ago (*1*) that the spectral and lifetime data discussed above could be measured in a straightforward way by means of apparatus and techniques originally developed for studying nuclear physics. Here is how.

An atom smasher accelerates individual atoms to high energy. A particular kind of atom smasher, the Van de Graaff electrostatic generator, is capable of accelerating virtually every atomic species to an energy which can be varied within wide limits and is extremely stable at any chosen value. Generally speaking, the accelerated particles lose a single electron at the start of the energizing process, and the particles emerge from the machine as ions with one positive charge. A magnet may be used to select a particular kind of particle out of the emergent beam, so that the chemical, and even the isotopic, purity of the particles striking the target is assured. If the target is thin enough so that the beam particles can pass right on through, there is a good chance of changing the particle's degree of ionization. Exactly what happens depends on the kind of beam particle, its energy, and the properties of the target. Figure 2 shows the ionization distribution resulting from sending oxygen through columns of argon gas, and Fig. 3 gives similar information for the stripping of electrons from bromine transmitted through a thin foil of carbon.

It seemed that these ionization distributions ought to be accompanied by a distribution in excitation. After all, the energy difference between ionization to some amount and excitation to levels in the previous charge stage is small. Hence we argued that, along with the production of, say, n-fold ionized particles, there should be some excited ions with only $(n - 1)$ charges. In this event the excited particles would have to relinquish their excess energy as light. This seemed to offer a way of producing spectra from multiply ionized atoms.

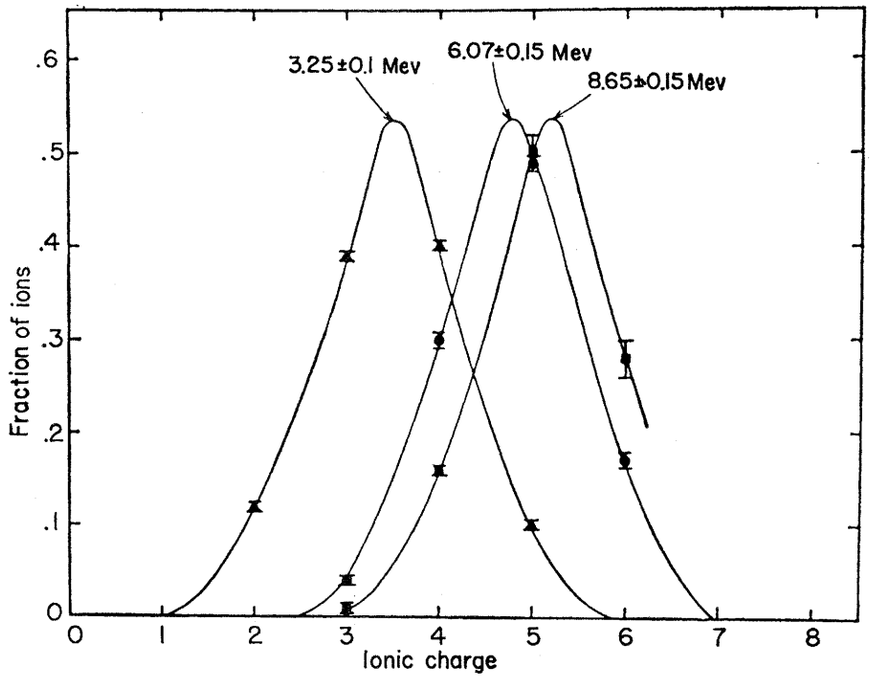

Fig. 2. Ionization distribution resulting from sending singly charged, positive ions of oxygen through argon gas. The three curves pertain to three different incident energies (in millions of electron volts). [From E. L. Hubbard and E. J. Lauer, *Phys. Rev.* **98**, 1814 (1955)]

The use of a foil for the target is preferable to a gas because the gas itself gives off light, whereas the foil does not. Also, the point at which the beam atoms are ionized and excited is closely determinable with a foil target but not with a column of gas.

Initial Experiment

The first experiment to test this method was made with an accelerator made available by the High Voltage Engineering Corporation (*2*). A. B. Meinel, director of Steward Observatory, accompanied me. He carried the spectrograph he had built for spectral studies of faint nebulae, and I brought along a target chamber designed on Tuesday and fabricated by Friday of the same week (*3*). The first measurements were successful, and data were quickly obtained on eight elements (hydrogen, helium, carbon, nitrogen, oxygen, argon, krypton, and xenon). The last photographic plate was developed exactly 1 week after the High Voltage Corporation offered use of its accelerator.

The principal finding was that the fast beams are a practical source of light from a great variety of elements in various stages of ionization. A second result, entirely unexpected, is of astrophysical interest. In these experiments we did not have a device for sorting out the different kinds of particles present in the incident beam. Also, the kind of gas admitted into the ion source was changed so rapidly that each new gas was contaminated by a residue of previous gases. Thus we accelerated acetylene, for a source of carbon, then oxygen, and then nitrogen, so the beam contained mostly nitrogen, but hydrogen, carbon, and oxygen as well. Figure 4 (top) shows a microphotometer tracing of a nitrogen plate. Clearly, many spectral lines were excited; our identifications are indicated on the tracing. Figure 4 (bottom) is a similar spectral study, but for the light emitted by Nova Herculis 1960, as observed by George Wallerstein. Note the similarity of position of the maxima in the two curves.

Because of this similarity it was suggested (*4*) that the nova light may have been reproduced in the laboratory. The fact that the heights of the peaks do not correspond is not regarded as significant, since, in the laboratory work, the heights depend on beam energy. If the suggestion is valid, it should be possible to get a better match of heights through a proper choice of beam energy. It also follows that the light emitted by the nova may be due in part to the motion of highly energetic particles through the atmosphere of the exploding star, not solely to the temperature at the stellar surface.

There are other stars in which fast particles are likely to be present. Even the sun, which is a quiet star, emits a steady stream of protons, the output

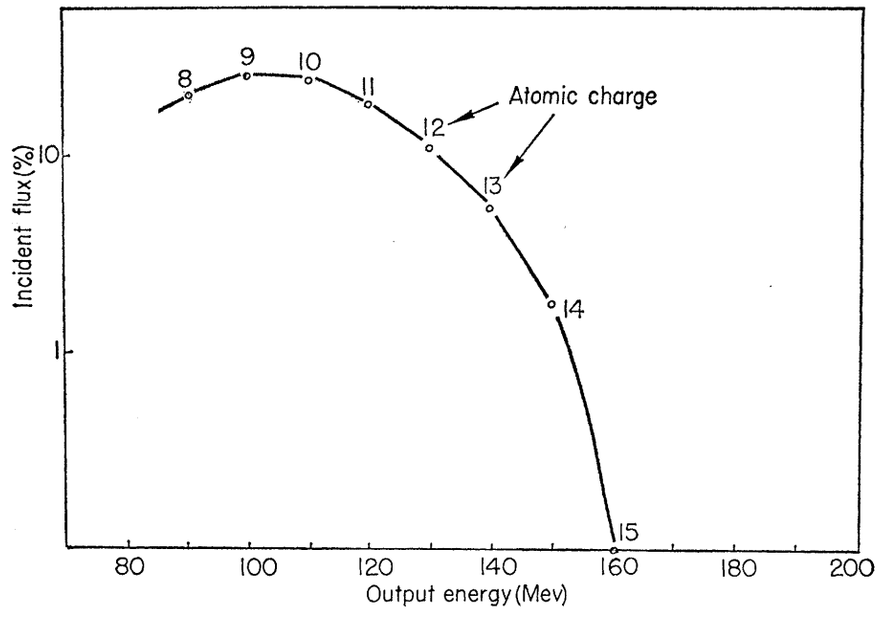

Fig. 3. Ionization distribution resulting from sending singly charged, positive ions of bromine, with an initial energy of 10^6 electron volts, through a thin carbon foil. (The abscissa gives the ultimate particle energy following further acceleration of the multiply ionized particles.) [From E. Almquist, M. A. Clark, J. A. Kuehner, A. E. Litherland, *Can. J. Phys.* **40**, 954 (1962)]

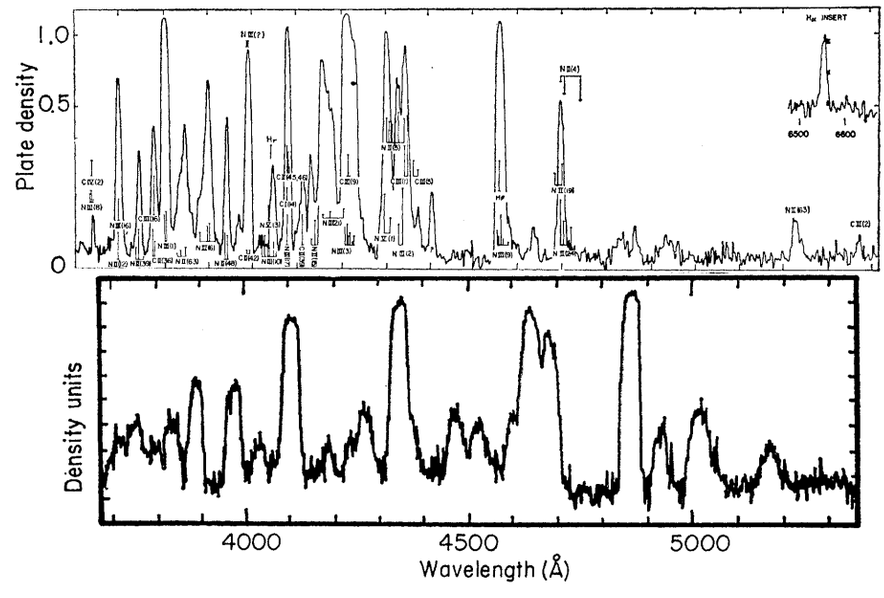

Fig. 4. (Top) Microphotometer tracing of photograph of resolved light from a fast beam of nitrogen and other elements. [From Bashkin and Meinel (*4*)] (Bottom) Microphotometer tracing of a photograph of resolved light from Nova Herculis 1960. [Data obtained by G. Wallerstein and published by A. B. Meinel, *Astrophys. J.* **137**, 3 (1963)]

being 3×10^{37} protons per year, with a proton energy above 10^7 electron volts (*5*). It seems reasonable to believe that a large number of fast particles are to be found at the solar surface. Should they be present at the proper place, they could contribute significantly to the sun's emission spectrum.

Indeed, it has often been suggested (*6*) that the relative abundances of elements in certain stars other than the sun are the result of nuclear reactions in the stellar atmosphere. Protons and helium nuclei, accelerated by changing magnetic fields, presumably reached energies of at least 10^8 electron volts. These projectiles, speeding through the ambient stellar gas, caused the nuclear events which, according to the speculations, altered the chemical composition of the star.

I merely point out that those fast particles, if they exist, must generate the light characteristic of multiply ionized atoms. This light, generally of very short wavelength, is absorbed by the air and can be observed only in a vacuum. Consequently, one test of the foregoing theory is to look for this kind of light in stars where nuclear reactions are believed to be occurring. The T Tauri stars are thought to be of this kind. Perhaps experiments with an orbiting astronomical observatory equipped to detect light in the vacuum ultraviolet and commanded to analyze the T Tauri spectra would put this theory on a more quantitative basis, or lay it to rest.

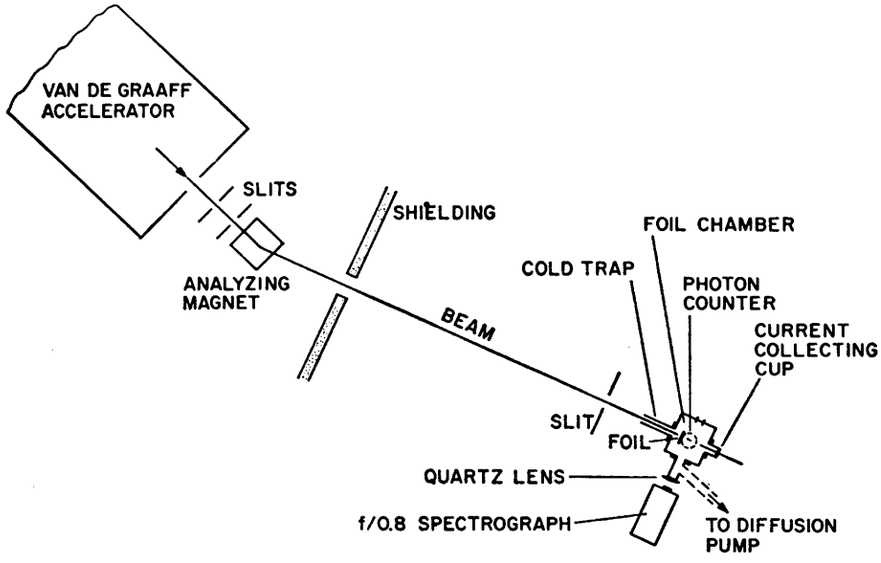

Fig. 5. Schematic diagram of the target arrangement used at the Naval Research Laboratory.

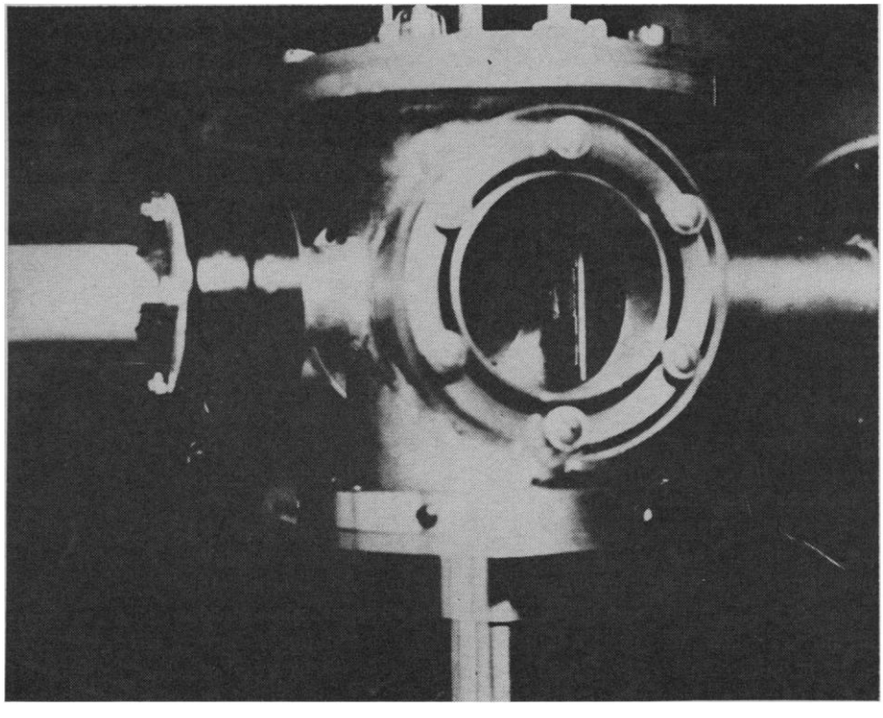

Fig. 6. The target chamber. A lucite window provides a view of the foil holder inside the chamber. The beam enters from the right.

Later Experiments

The experiments made with the High Voltage Corporation accelerator showed that the proposed method was practical, but they were not quantitatively satisfactory. A second series, in which much better results were obtained, was conducted at the Naval Research Laboratory (NRL); collaborating with us in this series were Philip Malmberg, of the NRL Nucleonics Division, and Shelby Tilford, of the E. O. Hulburt Center for Space Research (*7*).

Figure 5 illustrates the target arrangement at the Naval Research Laboratory. Figure 6 shows the target chamber, the interior being visible through a transparent window. The foil holder is in place. Figure 7 shows the effect of sending an energetic beam of nitrogen through a thin carbon foil. The particle beam, moving from right to left, is wholly invisible on entering the target chamber but is rendered luminous by interaction with the carbon atoms in the foil.

Two principal features may be seen in the glowing beam.

1) There is a bright spot where the beam intersects the foil. The light from the bright spot has been examined only cursorily; it seems to have a continuous wavelength distribution. Such bright spots have been seen by others (*8*) who have sent fast electrons or protons through thin foils. Presumably the electromagnetic shock wave carried by the beam particles sets the foil electrons into oscillation. The oscilla-

tory energy is eventually lost as light which emerges from the foil.

2) The light intensity declines as the beam gets further from the foil.

We have given particular attention to the beam of light. We have resolved that light into its component colors with the help of one of Meinel's grating spectrographs. The spectrograph was arranged so that the intensity variations in the beam were recorded in the constituent wavelengths. A typical spectrum is shown in Fig. 8.

In Fig. 8 the beam is traveling upward. The small blobs at the base are poorly focused comparison spectra of iron and neon. The roughly triangular streaks represent the data, which, in this case, come from oxygen particles with an incident energy of 10^6 electron volts. The intensity of the particle beam was small (0.8 microampere), and the exposure time was only 18.6 minutes, but, even so, many of the spectral lines were badly overexposed. Spectral data on oxygen were obtained in the region from 2500 to 7500 angstroms; only a portion of the information is displayed in Fig. 8.

It is obvious that numerous electron transitions have been observed. Prior to the first experiment we thought it possible that the collisions might create such unusual kinds of light that the energy levels responsible for the emission could not be readily recognized. Fortunately, all the observed lines have been identified with lines listed in standard tables. Perhaps it seems from this that nothing new has been accomplished, but consider the following points.

As Fig. 8 shows, the lengths of the spectral lines are not all the same. Some intense lines are long, others are short. Similar variations in length occur for the weak lines. Now, the particles are all excited at the same place—namely, at the foil. As time passes, the excited electrons relinquish their energy, returning to lower energy levels. Hence, with the passage of time, fewer of the particles excited at the foil remain energized, and the intensity of the light therefore declines. However, the particles are all moving away from the foil at constant speeds. Consequently, the decay of light intensity with time is convertible into decay of light intensity with distance, and the lengths of the spectral lines are directly correlated with the lifetimes of the excited energy levels. Figure 8, in fact, contains a large fraction of all the data on atomic lifetimes that physics had hitherto produced, but this is only a small part of what has already been obtained in experiments of the type described. Thus a means has been developed of solving the more difficult of the two outstanding problems mentioned earlier—that of measuring the lifetimes of atomic energy levels.

There is still need for better data on lifetimes. For one thing, photographic plates are not well suited for the measurement of intensities. Photoelectric recording has been used (*9*) in connection with the vacuum ultraviolet work discussed below. In that work, the first measurements of energy-level lifetimes were made. One such lifetime was found to be 1.3×10^{-9} sec; another, 1.7×10^{-10} sec.

Since the spectral lines are not obscured by any underlying continuum radiation, good measurements of absolute intensities should yield not only the lifetimes of the excited states but also the absolute probability of formation of each excited state. This information plays an important role in the theory of the excitation process. It also promises a method of producing absolute-intensity standards over a wide range of wavelengths.

Difficulties

In this work we encountered two difficulties which affected the accuracy of the data and which can be avoided through greater care in setting up the equipment: (i) the comparison spectra were not in good focus; (ii) the spectrograph slit was not uniformly illuminated. The first of these difficulties complicated the wavelength determinations; the second caused the spectral lines to have triangular shapes.

The other major problem—the excitation of multiply ionized atoms—has also been solved. Justification for this statement is the fact that the degree of ionization can be increased merely by increasing the energy of the particles in the beam, as is evident from Fig. 2. Until very recently, measurements had been carried out at energies of 2×10^6 electron volts or less. This restriction was due partly to lack of accelerator time in which to exploit all the possibilities inherent in the method and partly to the fact that the detecting equipment was limited to the wavelength region above 2500 angstroms. As the stage of ionization goes up, most of the transitions will lie deeper and deeper in the ultraviolet, and detection in these regions requires a different kind of analyzing device.

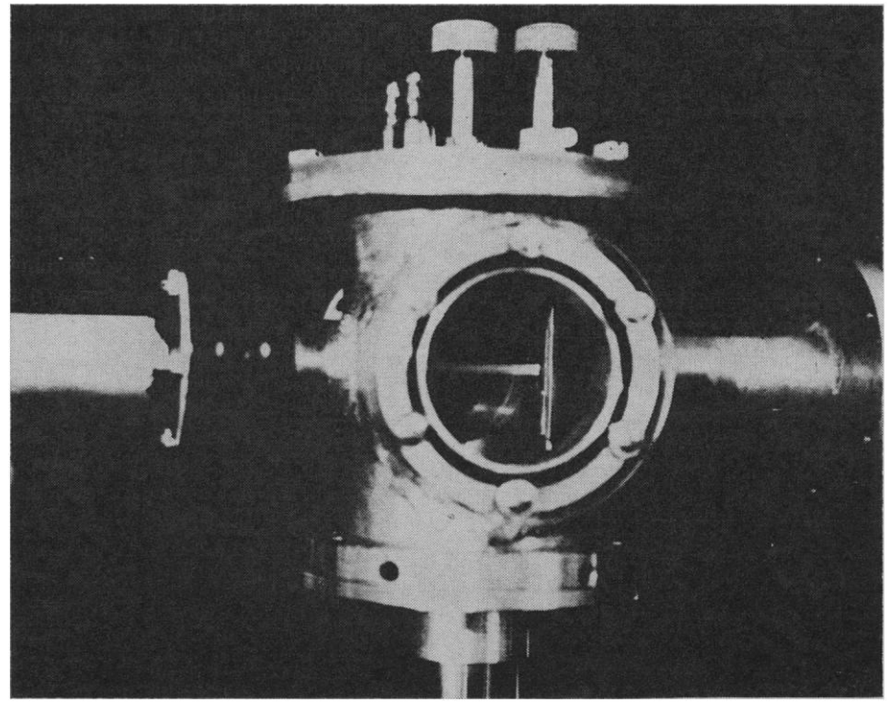

Fig. 7. Photograph of a nitrogen beam, traveling from right to left, being rendered visible by interactions in the carbon foil. There is a high vacuum in the target chamber.

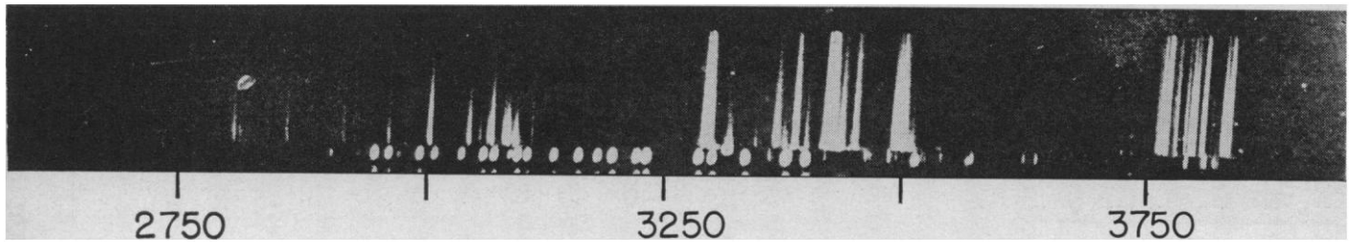

Fig. 8. Spectrum of oxygen, obtained with the beam method. The beam is traveling upward. The carbon foil is at the base of the lines. The blobs below the foil are poorly focused comparison spectra. Wavelengths are in angstroms.

The first data (*9*) for the vacuum ultraviolet were obtained in the course of another week's work at the High Voltage Engineering Corporation. The company provided an accelerator which ejected doubly and triply ionized neon ions at high energy. The ultraviolet radiations these particles emitted after going through a carbon foil were observed by means of a grating spectrometer such as is normally used in rocket flights. Fourteen strong lines, coming from neon ions with charge stages ranging from 1 through 6, were identified. The wavelengths were between 350 and 600 angstroms. We are now confident that the beam technique can be used over the entire wavelength range of interest.

Goals

One of the immediate goals is to simulate the spectra seen in the solar corona. Since the beam sources are chemically pure and controllable, the element which emits a certain line is definitely known. Should the laboratory spectrum and the solar spectrum coincide, the element identification will have been made.

Since the beam source is at room temperature and ground electrical potential, it is relatively easy to use auxiliary equipment. Thus, the beam can be passed through a magnetic field to provide information on the structure of the individual energy levels. Moreover, if the beam moves at right angles to the magnetic field, the charged particles encounter an equivalent electric field which can reach several hundred thousand volts per centimeter, a value virtually impossible to establish and maintain by means of traditional techniques. The electric field affects the wavelengths of the spectral lines in a way which depends on the character of the emitting energy level, so that the most intimate features of the energy levels become subject to careful scrutiny.

One interesting experiment already performed proves the practicality of using auxiliary electromagnetic devices. As noted above, the customary means of identifying the charge stage from which a given spectral line is emitted is by theoretical calculations. An experimental approach has now been developed (*10*). A beam, excited on passing through a foil, was sent between two parallel metal plates 0.5 centimeter apart. A direct-current potential difference of 35,000 volts was

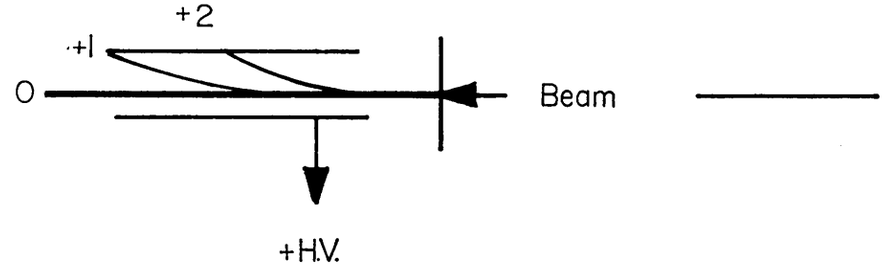

Fig. 9. Schematic representation of beam splitting by electrostatic means.

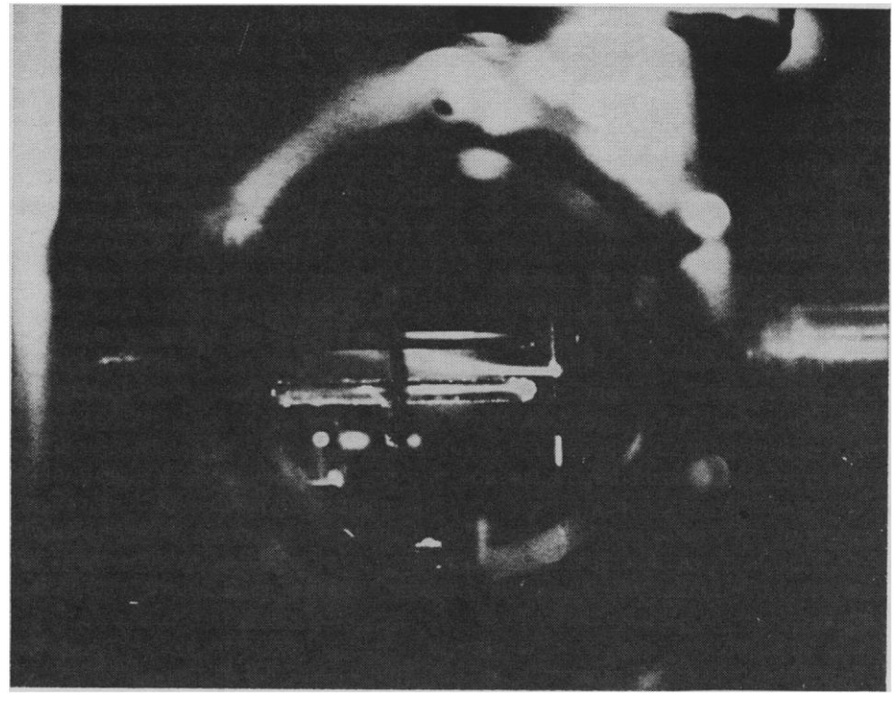

Fig 10. Photograph of split beams of nitrogen. The dark vertical line behind which the N^{++} beam strikes the upper plate is a high-voltage lead. The N^{+} beam may be seen hitting the upper plate to the left of that lead.

Fig. 11. Three spectral lines of hydrogen shown as slanted streaks between short comparison spectra. Wavelengths are in angstroms.

applied to the plates. The charged particles in the beam were deflected by the electric field and traveled along parabolic paths which differed for different charges. The process is shown schematically in Fig. 9, and a photograph of an actual case appears in Fig. 10. The beam is composed of nitrogen ions with an energy of 10^6 electron volts. The metal plates glow under the bombardment by electrons ejected from the foil, but two faint parabolic trajectories, due, respectively, to singly and doubly charged nitrogen ions, are visible to the eye. These separated beams have been analyzed with a spectrograph and have yielded the first spectra to be obtained from pure sources of charged emitters with a single charge other than zero. Malmberg has recently considerably improved this phase of the research.

There are some limitations to this approach. Clearly, if the lifetimes are too short, the path will not be long enough to permit clean separation of the light. Also, the application of an electric field shortens the life of any excited state. Nonetheless, this kind of separation, which may be achieved also by applying a magnetic field, should lead to much simplification in spectral analysis.

The spectral lines in Fig. 8 are slanted in the direction of long wavelength. This effect may be clearly seen in Fig. 11, which shows three spectral lines from hydrogen. The slant is due to the familiar Doppler phenomenon: the observed wavelength from a moving emitter changes as the emitter approaches or recedes from the viewer. The Doppler shift has been produced to a marked degree in these experiments because of the high speed (about 1 percent of the speed of light) of the emitters. Incidentally, it may be feasible to use these fast beams to carry out experiments on the fundamentals of relativity theory.

Conclusion

The new spectroscopy is in its infancy, and many fascinating aspects are yet to be studied. The properties of thin films may be studied by means of the excitation they induce in a given kind of beam. The production of ions with but a single electron offers a means of carefully mapping the nuclear charge distribution without the complications introduced by the normal complement of electrons. The study of high-purity, multiply ionized particles should make for better temperature determinations in hot plasmas. Possibly the data on lifetimes and modes of decay of excited energy levels may assist in the quantitative assignment of element abundances in the stars. One can even attempt to use the glowing beams as sources for absorption spectroscopy. The method seems to permit study of every stage of excitation for every stage of ionization for every element in the periodic table. Practical problems may interfere with so complete a study, but a major extension of our knowledge of atomic structure seems to be at hand.

References and Notes

1. The author's first formal presentation of these ideas was made at the 3rd International Accelerator Conference in Boston, on 11 November 1963. The paper was later published: S. Bashkin, *Nucl. Instr. Methods* **28**, 88 (1964). An experiment of this nature was performed by L. Kay [*Phys. Letters* **5**, 36 (1963)].
2. The High Voltage Engineering Corporation offered us several days of free use of one of its accelerators. The University of Arizona made travel money available.
3. Foils were provided by Dr. Alex Langsdorf of the Argonne National Laboratory, and Mr. Anthony Luongo of Professor W. W. Buechner's Laboratory at the Massachusetts Institute of Technology.
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