# Beam-Foil Techniques: New Approach to Atomic Lifetimes

Many scientists are combining the tools of two disparate disciplines, nuclear physics and classical spectroscopy, in order to attack problems apparently as unrelated as models of the interior of the sun and the structures of the simplest atoms.

The key to the new technique is that the pure, energetic beams of ions which are essential to the study of some aspects of nuclear structure can be used to complement conventional techniques for the study of atomic structure. The purity of atomic species produced in such beams, together with the simplicity of measuring the lifetimes of atoms decaying in flight, offers several advantages compared to the study of such lifetimes with conventional techniques. In the beam-foil technique, excited atomic states are produced in a beam as it passes through a thin foil. As nuclear physicists gained the skills necessary to produce beams of atoms other than hydrogen, the new technique could be applied to most atomic systems. According to Stanley Bashkin, of the University of Arizona, Tucson, who performed one of the first beam-foil experiments in 1963, almost as many lifetimes of atomic states have now been measured by the beam-foil method as had been measured previously by other methods.

Measurements of atomic lifetimes may be used by scientists to interpret many phenomena. Louis Brown of the Carnegie Institution of Washington, Department of Terrestrial Magnetism (DTM), reports that he has had more requests for reprints for a paper giving lifetimes of neon and argon than for any other paper he has published; presumably most of the interest was shown by physicists who were looking for new laser modes in those gases. Another beam-foil measurement, which determined lifetimes of atomic states in iron, has had a particularly significant impact on astrophysics. Ward Whaling and associates at the California Institute of Technology, Pasadena, obtained lifetime values 5 to 20 times longer than the results of some earlier measurements. At about the time of Whaling's work several measurements repeated with conventional techniques also suggested that the original values were in error. Although the beam-foil experiment was not the first to yield new values, the fact that it was a measurement by a completely different technique appears to have swung the balance of judgment of many scientists toward acceptance of longer lifetimes.

As a result of the increased values for the lifetimes of the states of iron, many astronomers estimate that the abundance of iron in the photosphere of the sun should be increased by a factor of 10. This change has the welcome result of eliminating discrepancies between the iron abundance in the photosphere and in the solar corona. However, the new value has made the perplexingly low fluxes of neutrinos (*Science*, 4 February 1972, p. 505) even more difficult to reconcile with current models of the sun.

Although beam-foil measurements can be used to study neutral atoms, as in the case of iron, the techniques appear to be making unique contributions to the understanding of highly ionized atoms. When a continuous stream of high-velocity ions passes through a very thin solid film (carbon about 10 micrometers thick is often used), collisions with the foil cause an exchange of electrons between the moving ion and the foil. If the ion is moving through the foil faster than the mean orbital velocity of some of the outermost electrons, those electrons are stripped from the ion. If the energy of the beam of ions is high enough, it may be possible to strip off all the electrons. Because the beam moves through a vacuum, there is very little chance that the ion will recapture any electrons.

Not all ions are formed in the ground state. Ions that are formed in an excited state will subsequently decay to the ground state and emit radiation. Thus a beam of ions that was invisible before hitting the foil may emit light after passing through it (Fig. 1). As all the excited atoms decay, the intensity of light coming from the beam dwindles until the beam is finally invisible again. The mean distance that the atoms of the beam travel before they decay can be measured by detecting the radiation with a spectrograph (for visible or ultraviolet light) or a proportional counter (for detecting x-rays). The mean distance, called a decay length, can be readily translated into a lifetime because the speed of the beam is known. Lifetimes of atomic systems between 0.5 and 100 nanoseconds have been measured in this way.

Highly ionized atoms can also be produced in electric discharges in which a large current produces a high-temperature plasma, but several problems make absolute measurements difficult. (Transition probabilities rather than lifetimes are typically measured in an experiment with an electric discharge. The two quantities are related, but several transition probabilities are generally associated with one lifetime.) One problem with an electric discharge is that contaminants may produce radiation that can be confused with the radiation from the desired atomic species. In addition, some transitions may go unobserved because the atoms desired for study may be de-excited by collisions with other atoms rather than by detectable radiation. Another problem with measuring accurate transition probabilities in a discharge experiment is determining the exact number of atoms in the discharge.

Beam-foil measurements, in contrast, depend only on the accurate measurement of a decay length and an ion velocity. However, there are difficulties with the beam-foil measurements also. For instance, the measurement of a decay length is often not characteristic of the lifetime of a single state, but of the lifetimes of several states decaying in sequence. Whaling, among others, has observed that relative probabilities for many atomic transitions can be accurately measured with an electrical discharge (relative measurements do not require knowledge of the exact number of atoms in a discharge), and then one lifetime can be accurately measured by the beam-foil technique in order to determine all the transition probabilities in absolute terms. Because the electric discharge technique cannot measure lifetimes and the beam-foil technique cannot measure relative transition probabilities, the two techniques are complementary.

Studies of highly ionized atoms have

provided several new measurements of the structure of one- and two-electron atoms. These simple atoms have been the testing ground for theories of atomic structure in the past. The accurate prediction of the energy levels of the one-electron hydrogen atom (to 1 part in $10^6$) is, many scientists think, one of the great triumphs of the basic (Schroedinger) formulation of quantum mechanics. A more sophisticated theory of quantum mechanics that incorporates relativistic effects is the Dirac theory. More sophisticated still, the most complete theory of electromagnetic interactions is the theory of quantum electrodynamics (QED), in which not only are the electrons in atomic systems described by quantum equations, but also the behavior of the electromagnetic field under the stimulus of electron motions is quantized as well. Although such a broad description is not needed to explain most quantum and electrooptical effects, quantum electrodynamics has had outstanding success in describing the exact magnetic moment of the electron and the separation in energy of two closely spaced states of hydrogen (the Lamb shift) which neither the nonrelativistic nor the relativistic theories of quantum mechanics can account for.

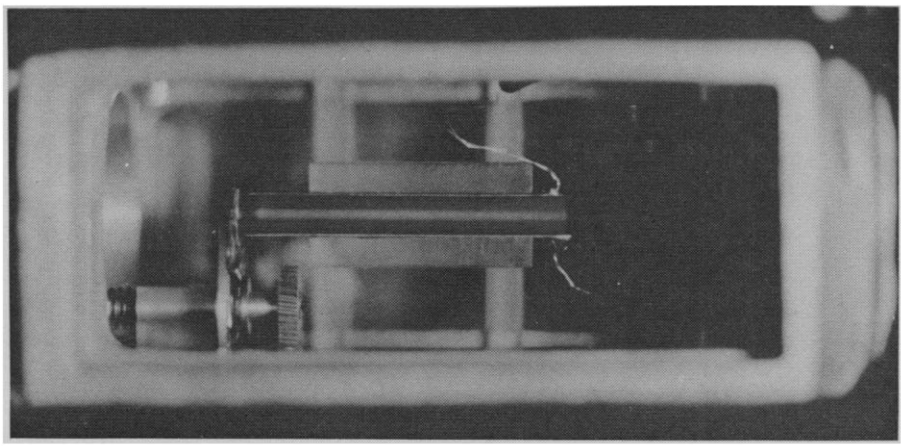

Fig. 1. The tapered ray of light in the center of the photograph is emitted by a beam of atoms moving from left to right. The atoms are invisible before they strike a thin foil (on a geared wheel at the left), but become visible as excited states emit light. The lifetime is approximately the time for the atoms to travel the length of the tapered ray.

#### Testing Atomic Theories

Richard Marrus and Robert Schmieder at the University of California, Berkeley, have confirmed the applicability of the nonrelativistic theory of quantum mechanics to the description of a particularly long-lived state in one-electron argon. This state (called metastable and identified as $^2S_{\frac{1}{2}}$ in spectroscopic notation) cannot decay by the normal sort of electromagnetic transition, which is electric dipole radiation, because angular momentum would not be conserved in the transition. Instead of decaying by the emission of one photon, the metastable state decays by the emission of two photons, as was predicted in 1940 by Gregory Breit and Edward Teller. These physicists showed how to calculate the lifetime of the metastable state, which occurs in all one-electron atoms; but no one had been able to measure it accurately for atoms like hydrogen because the atom lives so long that even in ultrahigh vacuums it is more likely to decay by collisions with other atoms than by emission of two photons. Marrus and Schmieder were able to measure the lifetime of the analogous metastable state in one-electron argon, however, because the lifetime decreases rapidly with increasing nuclear charge. The result agreed well with the original predictions made in 1940.

Other experiments on the lifetimes of two-electron argon atoms raised the question of whether the Dirac theory of quantum mechanics (the theory of intermediate complexity) was sufficient for this problem. Although physicists believe that QED is the most exact theory of atomic structure, there are very few measurements that are sensitive enough to detect differences between the predictions of the Dirac theory and QED.

The decay of a state of two-electron argon, as observed at Berkeley with an argon beam with an energy of 400 million electron volts, proceeds by the emission of magnetic dipole radiation. This type of radiation is rare in atomic spectra. For the state that was observed (the $2^3S_1$) no magnetic dipole radiation is predicted at all in the simplest (Schroedinger) theory of quantum mechanics. The Dirac theory predicts magnetic dipole radiation, as observed, but the lifetime that Marrus and Schmieder measured is 20 percent lower than the value predicted by the Dirac theory. According to Gerald Feinberg of Columbia University, New York, a discrepancy of about 5 percent between the measured and calculated values might have been expected because the calculation is not exact, but represents only the first term in a series of successively smaller terms. The fact that the discrepancy is significantly larger than 5 percent may indicate, Feinberg says, not that the calculation is inexact, but that the Dirac theory itself is not complete enough to describe the phenomenon. In one perspective, Feinberg notes, agreement to 20 percent is a "very pleasant thing to have gotten," but if further refinements of both the experiments and calculations continue to result in a discrepancy, this could be the first experimental evidence for the usefulness of the theory of QED with respect to atomic lifetimes. Until now, the only atomic phenomenon requiring a tedious QED calculation has been the Lamb shift.

Other physicists are testing quantum electrodynamic theory directly with the beam-foil technique by measuring the Lamb shift in atoms with ever larger nuclear charges. Marvin Leventhal and Daniel Murnick at the Bell Telephone Laboratories, Murray Hill, New Jersey, and Henry Kugel at Rutgers University, New Brunswick, New Jersey, have measured the Lamb shifts in one-electron carbon and oxygen. The results have confirmed the validity of quantum electrodynamics to the accuracy of the experiments (about 1 percent).

As the funding of research in nuclear physics decreases, the demand for access to the many Van de Graaff accelerators in the United States is also slackening, and accelerators are becoming more available for interdisciplinary research. Indeed, the needs of a scientist doing beam-foil research do not always run to the newest or the most powerful accelerators. Two of the oldest Van de Graaff accelerators in the country, one built in 1939 at Caltech and the other about the same time at DTM, are still being used to do valuable experiments.

—WILLIAM D. METZ