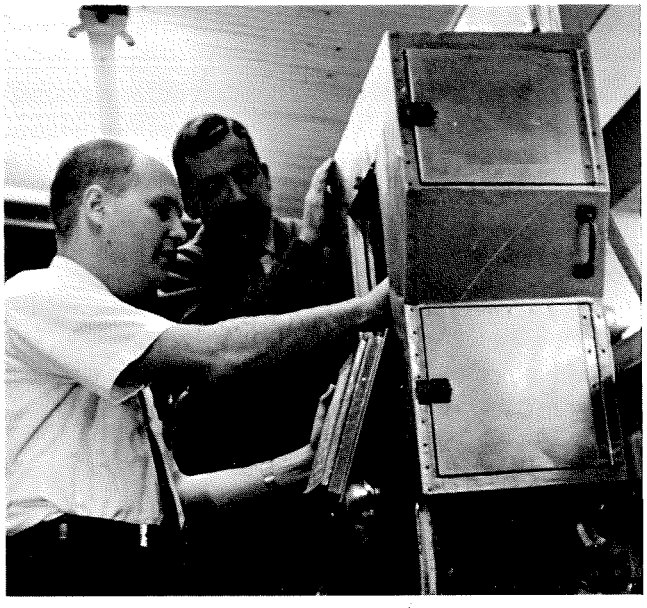
Atomic Spectroscopy and the Abundance of the Elements

by Ward Whaling and George M. Lawrence

The Kellogg Laboratory is bringing some of the techniques of nuclear physics to bear on problems in the optical spectroscopy of atoms. This activity is a natural development of our longstanding interest in nuclear physics and nuclear astrophysics, and stems from the fundamental role that atomic spectroscopy plays in present-day astrophysics.

Astronomers learned long ago how to analyze the wavelengths of starlight to identify the elements present in a star, an amazing accomplishment that has made possible the modern science of astrophysics. As soon as they were able to make qualitative analyses of a star's composition, the next step was inevitable and immediate: to make a *quantitative* analysis to find *how much* of each element is present.

As might be expected, quantitative analysis has turned out to be more difficult, but for reasons that are not widely known outside the ranks of professional astronomers. Whereas the identification of an element requires only the measurement of a characteristic wavelength in the starlight, quantitative analysis requires the measurement of the number of photons of the characteristic wavelength, plus a knowledge of certain properties of the radiating atom, properties that can be measured in the laboratory.



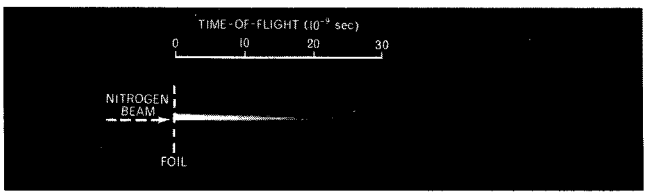
George M. Lawrence, visiting associate in physics from the Douglas Advanced Research Laboratories, and Ward Whaling, professor of physics.

As astronomers have tried to measure elemental abundances, they have found that the accuracy and reliability of their results is limited not by the difficulty of the astronomical observations but frequently by our meager knowledge of atomic physics. Except for the simplest atoms, we don't know enough about how atoms radiate and, in particular, how fast they radiate, and it is this barrier which our experiments seek to overcome. Since much of the research in Kellogg attempts to discover those nuclear processes that can account for the elemental abundances in stars, efforts to improve our knowledge of these abundances are clearly in keeping with our overall goals.

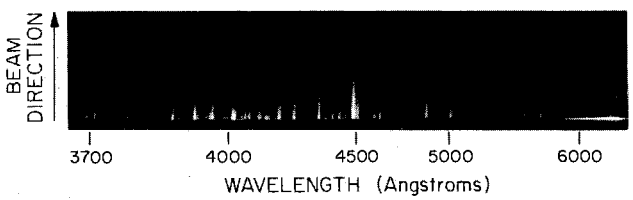
In spite of this motivation, it is not likely that we would have been diverted from the familiar field of nuclear research had not two other circumstances favored this diversion. First, a new and promising method of measuring the needed atomic properties was discovered by Stanley Bashkin, at one time a research fellow in the Kellogg Laboratory and now at the University of Arizona. His method makes use of high-velocity atomic beams that we can produce with the accelerators originally built for nuclear research. We had on hand the expensive facility needed to exploit this new technique. Second, and equally important, we had the collaboration of R. B. King, professor of physics, who had been measuring atomic properties of astrophysical interest and, in particular, atomic radiation rates ever since he came to Caltech in 1948 and even before that at the Mount Wilson Observatory. Without his patient introduction into the unwritten know-how of atomic spectroscopy, our first efforts in this unfamiliar field would have been slow and painful.

What is this new technique of measuring atomic radiation rates, and what do we mean by radiation rates? If an atom is raised to an excited level (for example, in a collision with another atom), it will remain in this excited level for a short time interval before it drops to a lower level, radiating a photon in the process. In atomic systems, this interval is typi-

cally 10^{-8} seconds—seemingly instantaneous by human standards—and it may be helpful to recall the analogous process in nuclear physics, i.e., radioactivity, where the time scale is more familiar. If we start with N(O) atoms at time t = O, all in the same excited level, the number that will survive for a time t is given by $N(t) = N(O)e^{-t/\tau}$ where τ is called the mean life of the level. The more familiar quantity, half-life, is just 0.69τ, and is the time in which one-half of the original number of atoms will decay. The mean life τ is characteristic of the particular level, and it is this quantity that we want to measure, since it determines how fast an atom will radiate once it has been raised to an excited level.



An invisible beam of nitrogen ions (N^+_2) approaches from the left with a velocity of about 10^8 cm/sec. and strikes a thin carbon foil. Collisions in the foil break up the molecule and excite the nitrogen atoms and ions into excited levels. Photons from the decay of these levels make the beam glow after it emerges from the foil. The gradual decay of this light is a measure of the lifetime of the excited level in the atom.



A spectrogram of the same nitrogen beam shown above. The beam now travels upward, and the time scale has been reduced. Each wavelength radiated by the beam appears as a separate image; the longer images signify longer lifetimes for the radiating level.

To measure these short time intervals, we use the distance traveled by the high-velocity beam as a clock. We excite the atom by shooting it through a thin foil, then see how far it travels before it decays, that is, how far from the foil the atom moves before the excited level radiates. The light that the atom radiates is the signal that tells us where the atom decayed, how far it went, and thus how long it lived, since we know how fast the atoms are moving.

Atoms are accelerated to high velocity (about 10^8 cm/sec) in our 2-million-volt electrostatic accelerator. After passing through magnetic and electrostatic deflectors which tell us the velocity of the beam, the atoms strike a thin carbon foil. The foil is only a few hundred atoms thick, and the energetic atoms pass through easily, but not without making many hundreds of collisions with atomic electrons in the foil, collisions in which the moving atom may absorb energy and be raised to an excited level. When the beam finally gets through the foil, each atom emerges in the level in which the last collision left it. Some will be in one level, some in another, and almost all of the atomic levels are represented in the emerging beam.

Once through the foil and into the vacuum where no more collisions take place, the excited atoms begin to decay. In each decay process a photon is emitted, and if these photons are collected in a camera, one obtains a photograph of the glowing beam (left). As more and more atoms return to the ground level, there are fewer and fewer atoms remaining that can radiate, and hence there are fewer photons, less light, and the beam becomes darker as it moves away from the foil. The finite lifetime of the atomic levels is clearly evident in the photograph; the time scale drawn on the photograph indicates the order of magnitude of the time interval.

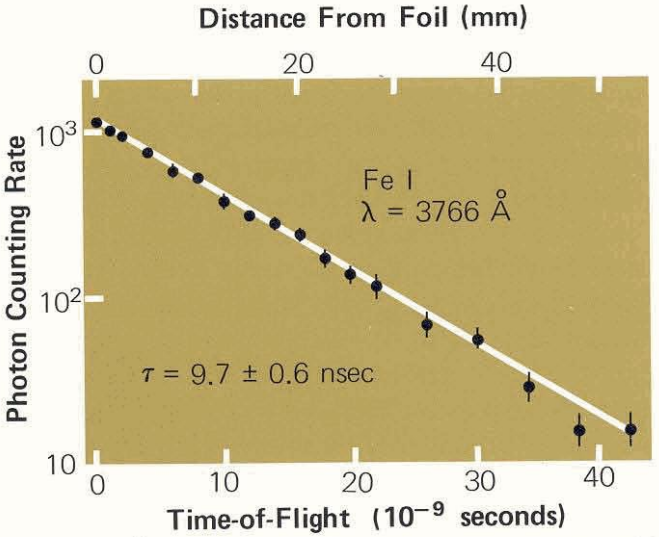
In order to measure the lifetime of a particular level, we need only isolate the characteristic wavelength radiated by atoms in that particular level. This separation can be achieved by photographing the glowing beam through a spectrograph. Different wavelengths appear at different positions in the spectrogram, and the beam is pictured over and over again. Each image corresponds to a different wavelength radiated by the beam, hence a different transition in the atom, and usually a different radiating level. The different lifetimes of different levels are quite evident in the spectrogram at the left.

In principle, it is possible to read the lifetimes of the different levels directly from the spectrogram by the standard methods of photographic photometry. We have found that we can achieve better precision by replacing the photographic plate with a photomultiplier tube which enables us to count the individual photons that enter the spectrometer. We restrict the field of view of the spectrometer so that it sees photons emitted only from a short segment of the glowing beam, and measure the counting rate as a function of distance from the foil. On the semilogarithmic plot, the exponential radioactive decay function becomes a straight line, with slope $(-1/\tau)$ that can be read directly from the graph.

We have chosen to look first at the iron spectrum and the lifetimes of levels in the iron atom. Iron recommends itself for several reasons: Except for the very lightest elements, iron is the most abundant element. Furthermore, its spectrum is unusually rich in lines, and iron lines are prominent features of nearly all astrophysical spectra. In the sun, more than 5,000 of the 13,000 identified lines are attributed to iron, and iron lines outnumber those of any other element by a factor of five. Because of this astrophysical interest, the iron spectrum has been extensively studied, and a great wealth of information already exists. Even a relatively few accurate lifetime measurements can make this existing information more valuable. Finally, there are interesting peculiarities in the observed iron abundance that have long perplexed astronomers. For example, the iron abundance in the sun is apparently about five times less than it is in meteorites, whereas other similar metals are about equally abundant in both. And there is disagreement, or surprising variation, even in the sun itself: The glowing disc (photosphere) appears to contain 10 to 15 times less iron than the corona, the halo around the sun that is visible when the disc is blanked out in a total eclipse. These and other longstanding problems put iron at the top of our list.

Our first results appear to justify our hopes and expectations. Light decay curves similar to the one shown in the graph (above right) have now been measured for six different levels in the iron atom. Our measured lifetimes differ from the previously accepted values by a factor of 4.7 ± 1.1, and, happily, this factor is in the right direction to make the meteoritic and solar abundance agree and to reduce the discrepancy between the chromospheric and the photospheric measurements.

Another phase of this research is now under way, although it is too early to tell what the results will be. As the iron atom shoots through the foil, colliding with electrons along its path, not only will the outer electrons be raised to excited levels, but, if the beam velocity is high enough, some collisions are so violent that electrons are shaken loose from the moving atom. As a result, the atoms emerge missing one or more electrons as charged iron ions, Fe^{+}, Fe^{++}, etc. These iron ions also have a characteristic spectrum, just as neutral atoms do, and in astrophysical applications these ionic spectra may be more interesting than the neutral atomic spectra. For example, on the sun's surface, more than 99 percent of the iron is in the form of singly charged ion Fe^{+}. In our high-velocity



The 3766Å transition in neutral iron observed with a 500 keV ion beam. The photon counting rate is shown at different distances from the foil. In this logarithmic graph, the exponential decay function appears as a straight line with a slope determined by the lifetime of the level which radiates this wavelength.

atomic beam we can produce ions of any desired charge by varying the beam velocity—the higher the velocity the higher the charge. We hope to be able to measure the lifetimes of levels in the singly and doubly charged iron ion, and it is reasonable to expect that these ionic lifetimes will provide another way of getting at the iron abundance in the sun.

Some of the results of these experiments may have interest quite apart from the abundance problem. More than half of the spectral lines that we see in the light from the glowing iron beam do not correspond to any known transition in the iron atom. These lines have never been seen before, and this is in spite of the fact that the iron spectrum has been more extensively studied than any other. The violent collisions in the foil excite levels that cannot be excited in the usual laboratory arc and spark, perhaps levels in which two or more electrons in the same atom are lifted into excited levels at the same time. Of course, it may turn out that such multiple excitation occurs nowhere else in nature, and our new lines are simply exotics of interest only to other atomic physicists. But it is our hope that these new wavelengths may lead to the identification of some of the many unknown lines observed in stellar spectra. Even in the sun, there are still 5,000 lines whose origin is unknown. It would be lots of fun to find in our beam spectra some of these unidentified lines, and it seems reasonable to expect that we will.