CHAPTER 5

The Bohr Atom

Somebody once said about the Greek language that Greek flies in the writings of Homer. The quantum idea started flying with the work of Danish physicist Niels Bohr published in the year 1913.

Scientists have an advantage in their creative work—they get to look at nature from the vantage point atop the "shoulders of giants." Besides Planck and Einstein, Niels Bohr had access to the shoulders of another giant, Lord Rutherford of Nelson, who dominated British physics in the first few decades of the 20^{th} century. Bohr was a postdoctoral research associate who came from Denmark to work with Rutherford.

Rutherford had a model of the atom, established in part from experimental observations, that intrigued Bohr no end. In this model the atoms consisted of electrons moving around nuclei; electrons were light objects that went around a central massive nucleus.

Almost all the mass of the atom resides in the nucleus; this was proven experimentally by Rutherford in an ingenious experiment. Before Rutherford, the English physicist J. J. Thompson, who discovered the electron back in 1887, had a model of the atom that proposed that atoms are like lumps of positive electric charge in which are immersed the negatively charged electron (so the overall atom is electrically neutral), very similar to little plums in a pudding. But when Rutherford hit the atoms of a gold foil with high-energy alpha particles of positive charge like a target shooter hits a target with bullets, he found no evidence at all in favor of the plum-pudding model. Most of the time the alpha particles just passed through the atoms undisturbed, suggesting that most of the atom is empty space. Most strangely, there were a few alphas that were deflected at very sharp angles, even coming back out where they entered.

Such large angle scattering (Figure 5.1), said Rutherford, can be explained only if the positive charge of the atom resides in a very tiny central core, the nucleus, which contains most of the mass of the atom. The positively charged alpha particles were being strongly repelled by the positively charged nucleus whenever they came close; hence the large angle scattering. And Rutherford backed up his argument with mathematics.

Since the electrons are drawn to the nucleus with an attractive electrical force following the inverse square law (the force decreases inversely as the square of the distance), it is very tempting to make a tiny solar system model of the atom, in which the electrons revolve around the nucleus like planets do around the sun, under the inverse square law of gravity. If the electrons moved with just the right range of velocities in their orbits, the electrical force has the right magnitude to make them go around. So this works out. The problem is this: an orbiting electron is an accelerated one because, in the least, the velocity keeps changing directions. According to Maxwell's theory of electromagnetism, a previously mentioned milestone of classical physics, an accelerated charge must radiate. Even that is all right–atoms do radiate light. But now as the electrons radiate, they must lose energy and spiral inward toward the nucleus. Eventually this leads to a collapse of the atom. This is similar to the collapse of our artificial satellites that go around the earth but lose energy to air friction so that their orbits decay.

So Rutherford's atom is not stable (Figure 5.2). Niels Bohr made it stable by injecting the quantum idea. Just as in the case of the quantum oscillator of Planck, the electrons of an atom must also exist only in quantized energy levels, or stationary orbits, because the orbits don't decay. The electron's orbits are quantized, discrete (Figure 5.3), said Bohr. Most importantly, Bohr realized that an electron does not radiate when in one of these stationary states, but only when it takes a jump from a higher to a lower energy level. The difference of energy between the levels involved in the transition comes out as light (or other electromagnetic waves). If the electron is in the lowest (ground) energy level, its ground state, then the atom is stable because the electron has no other lower energy level

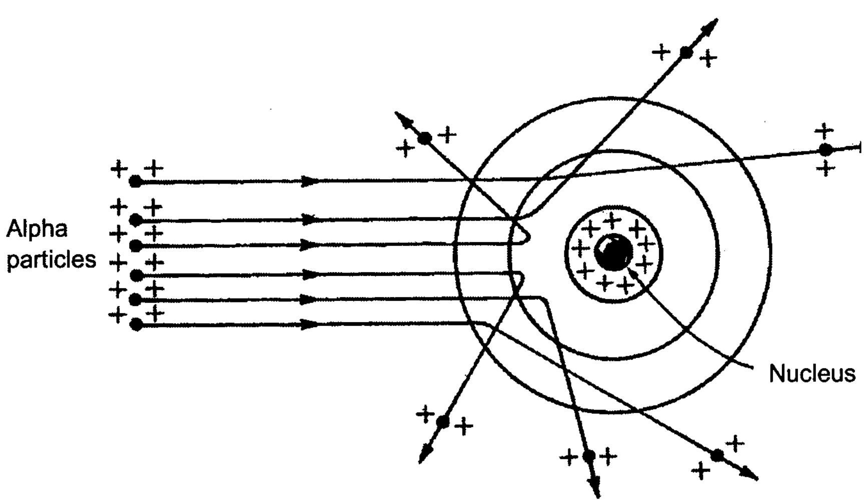

Figure 5.1
Rutherford's scattering experiment. Some of the alpha particles are turned backward by the repulsion of the heavy nuclear core of the gold target atoms.

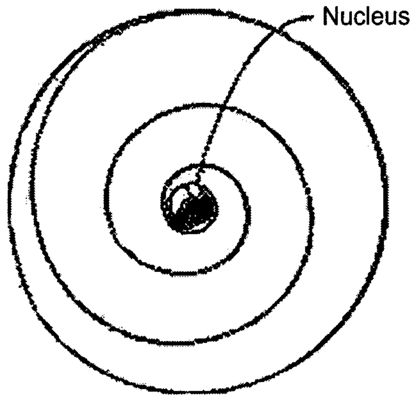

Figure 5.2
In Rutherford's original model of electrons going around a central nucleus, the electrons are destined to lose energy by radiation, and they will spiral inward, eventually falling into the nucleus.

to jump to. In this way the atom gains stability. An atom with all its electrons in their respective lowest permissible orbits is stable; there is no chance for any of the electrons to crash into the nucleus, declared Bohr, and physicists everywhere on earth greeted his discovery with a great sigh of relief. Look at a modern picture of the electron orbits of a stable gold atom based on the original idea of Bohr (Figure 5.4); doesn't it look like a Tibetan mandala? Indeed, Bohr's atom became the new mandala for physicists to meditate upon for quite a while.

But how does one describe the motion of an electron when in a stationary state, or while it is making a transition from one level to another? The stationary orbit is not like a planetary orbit, contrary to what you may think, and Niels Bohr was quite aware of this. This is why he carefully called the electronic states in the atom "stationary." An object in a classical orbit is not stationary; it changes with time. In contrast, for a stationary state nothing changes with time in any way that lends to a classical description, and Bohr was clear on that. I hope that now you are too.

Thus, if you ask questions like, "What does the electron do when in one of these stationary states?" you are wasting your time. We don't know. Maybe it improvises; maybe it is granted a certain amount of freedom of improvisation like somebody performing

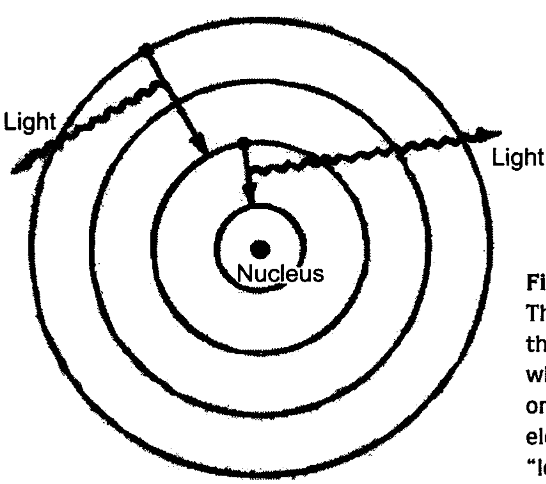

Figure 5.3
The electronic orbits of the Bohr atom. In this model, the electrons do not radiate while they are in one of these "stationary orbits." Radiation occurs only when an electron jumps from a "higher orbit" to a "lower" one, as shown.

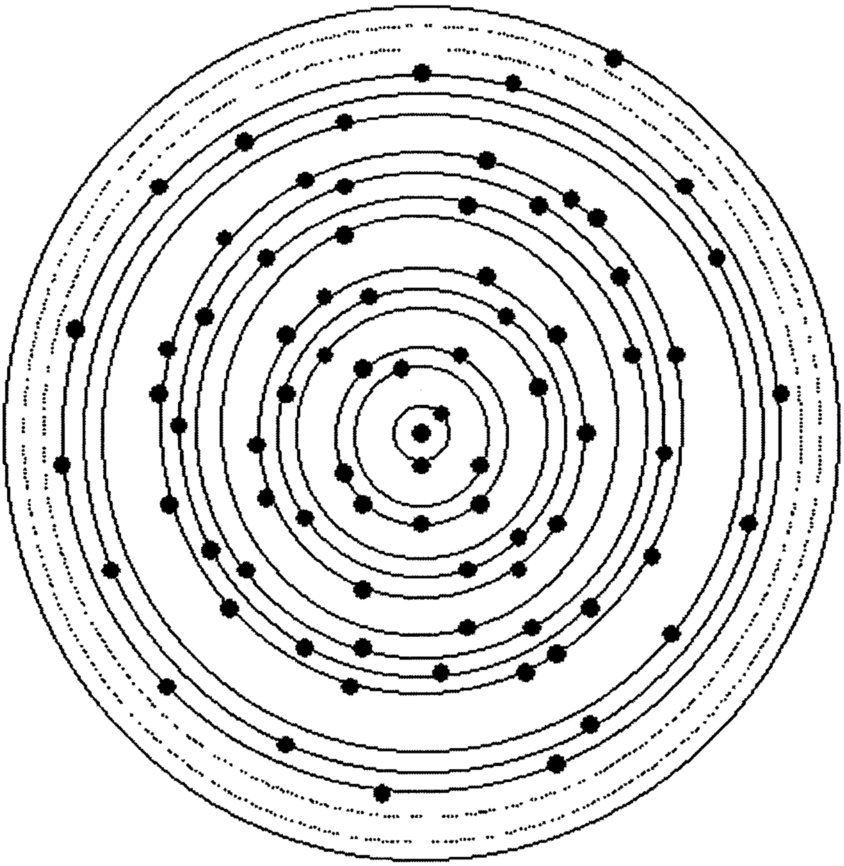

Figure 5.4
A modern picture of the electron orbits of a stable gold atom.

jazz music. Actually, we don't even much care to describe the electron while it is in one of these stationary states, because the electron doesn't do anything that is observable while in these states. So we allow ourselves to be a little ignorant (which a classical physicist abhors) because, as we will see later, the ignorance is imposed on us by nature. The situation is best described by the following quotation from *Science and the Common Understanding*, by American physicist Robert Oppenheimer:

> If we ask, for instance, whether the position of the electron remains the same, we must say 'no'; if we ask whether the position of the electron changes with time, we must say 'no'; if we ask whether the electron is at rest, we must say 'no'; if we ask whether it is in motion, we must say 'no.'

Likewise, when an electron takes a jump from one orbit to another, can we describe that jump in space-time? No. The electron never goes through the intervening space between orbits taking the usual time. The quantum jump is truly a discontinuous affair. Now the electron is here, and then it's there.

What is happening today is that we may be at the brink of verifying the discontinuous quantum leap of the electron in quantum phenomena. There is a phenomenon called *electron tunneling*: the electrons in transistors, for example, go across energy barriers. Do they tunnel through, as the name of the phenomenon suggests (no doubt due to the classical prejudice of the experimentalists who discovered the phenomenon), or do they leap across Bohr style, never going through the intervening space? Unfortunately, we cannot look at what is happening inside the barrier without destroying it; thus, until now, this has been a difficult matter to settle.

These days, though, very accurate time measurement enables us to measure the time taken by the electron for going across an energy barrier, and this time is found to be so small that the speed of the electron while crossing the energy barrier is inferred to be faster than that of light. But Einstein proved long ago as part of his theory of relativity that no material object can travel faster than the speed of light; the speed of light is the absolute speed limit in nature's highways (an idea that has also been verified by experimental data). So Bohr is right with his idea of the discontinuous quantum leap, the electrons in the tunneling phenomenon never go through the space of the energy barrier, they transcend it. Caution: this conclusion is still a little controversial.

Atoms and Philosophy

I hope you see the gaping opportunity that the idea of discontinuous quantum leaps creates to question some of the philosophical prejudices of classical physics. There are two kinds of motion in the world: *continuous motion*, as when the electron is describing a stationary orbit, and *discontinuous motion*, as when the electron takes a quantum leap from one orbit to another. During the first kind of motion, continuous motion, classical ideas such as causal continuity and determinism hold. But discontinuity is the harbinger of new ideas; it can be seen as a window through which consciousness and free will can enter physics and the physical world.

The point is this. Discontinuity means a breakdown of causal continuity. We cannot give a precise cause as to when the electron is going to make a jump. Or if there is more than one orbit or energy level to jump to (Figure 5.5), we cannot say precisely which orbit the electron is going to leap to or when. The electron's quantum leaping is acausal. So is it an act of free will of the electron?

In the beginning, Bohr and others did ponder such questions as, "Does the electron have free will?" But as the new physics took more accurate shape, it became clear that to ascribe to the electron free will is too simplistic; instead we have to bring ourselves into

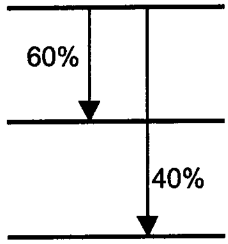

Figure 5.5
The observer does not know to which orbit the electron will jump, or when.

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