CHAPTER 3

Planck Takes a Quantum Leap

At the end of the 19th century, a series of discoveries was made in physics that called for a change in our worldview, a change that is still going on. How did it all begin? Let's discuss the crucial piece of experimental data that refused explanation on the basis of then-current beliefs of physics.

Toward the end of the 19th century, the belief was growing that classical physics was the last word in physics, that it explained everything, except maybe one or two small things. Among these "small" things was the phenomenon of ***blackbody radiation.***

If you can see yourself as a physicist at the turn of the century, you must also see yourself interested in understanding the phenomenon of blackbody radiation—how hot objects emit radiation. But as a physicist of classical vintage, you'd look at every phenomenon with the Newtonian conceptual lens that the universe is a classical machine consisting of parts that move continuously according to Newtonian laws. You'd believe that once you had all the necessary information about the movement of the parts and if you could figure out a few glitches, a few unknowns about the laws these parts obey, then you would be able to predict the future of the universe forever. So you would be perpetually troubled by those few glitches; the Newtonian science you would have known could not have prepared you to answer such questions as, "What is the law of emission of radiation from hot bodies?"

Imagine that it is winter, and as you puzzle over this question with great concentration while sitting in front of a glowing fire, your loved one is slightly impatient with your lack of attention toward him or her.

Loved one: Pass me another pillow.

You (passing the pillow): I just can't see through this. I can't figure out why we are not getting a good tan right now.

Loved one: (laughing): Well, a tan would be great. You know how much I love to have a tan. Then we could even justify using the fireplace in the summertime.

You: You see, my theory (it is called thermodynamics, my dear) says that the radiation from the fireplace should be as rich in the high frequencies—that's ultraviolet, sweetie, the invisible light that tans you—as sunlight is.

Loved one (frowning, deep in concentration): Go slow. What's frequency?

You (seeing the frown on your loved one's face): What's frequency? You see, radiation consists of electromagnetic waves; frequency tells you how rapidly the waves wiggle. But what makes the sunlight, and not the light from the fireplace, rich in these high frequencies? Look at this radiation-distribution curve (Figure 3.1, dotted line), based on my classical physics. The intensity keeps going up at the high-frequency end of the spectrum irrespective of the temperature of the emitter, with no attention to the experimental data.

Loved one (teasing): I didn't get all of that, but tell me, have you ever taken the temperature of an emitter, a feverish emitter? All right, I will be serious; yes, I see your point. The classical curve does seem to go up and up. But isn't there a song, "What Goes Up Must Come Down?" (Your loved one starts humming the tune.)

You (exasperated): But how?

And the conversation would end there, in exasperated frustration.

The graph in Figure 3.1 is referred to as the *frequency distribution curve* of blackbody radiation. Why this particular name? Blackbody radiation is the light and other electro-

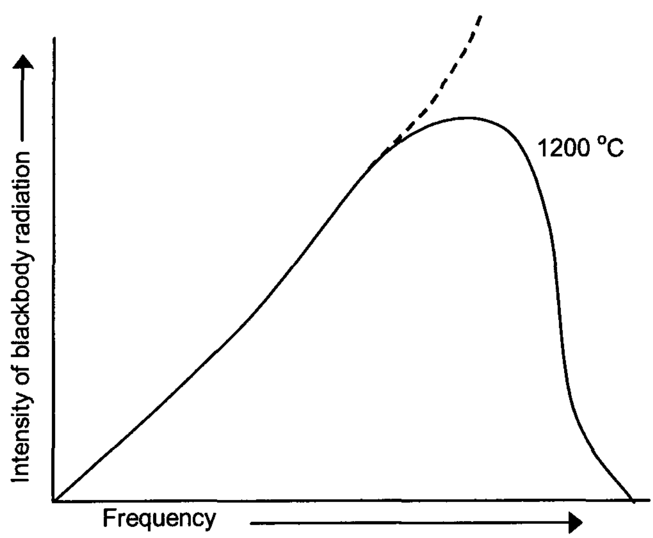

Figure 3.1
The spectrum of radiation emitted by an incandescent solid. The intensity rises to a maximum as the frequency increases and then tapers off at even higher frequencies. The dotted line shows the prediction of classical physics.

magnetic radiation that come out of a perfectly black enclosure, one that absorbs all the radiation that falls on it. When heated to a given temperature, the radiation of the blackbody theoretically can be shown to be dependent only on the temperature and on no other property of the body. It is thus an ideal source of radiation. The radiation spectrum of an incandescent solid is a close approximation to that of a blackbody. Figure 3.1 plots the intensity (energy from the blackbody falling per second and per unit area of an absorber) of radiation as a function of the frequency emitted.

The color (which is indicative of frequency) of the emitted light depends on the temperature of the substance. At low temperature the color is dull red (low frequency); then with increases in temperature the color changes to orange, yellow, white (signifying a mixture of the colors), and finally blue. The high frequencies begin to dominate as the temperature of the emitter increases. In fact, the peak of the distribution curve shifts to higher frequencies as the temperature increases (Figure 3.2), in accordance with what we see in the color. The peak frequency of maximum emission is indeed a signature of the temperature of the emitting body, and is used to quantitatively determine the temperatures of stars. As you may know, stars come in different colors depending on their temperatures: the coolest ones are dull red, and then we find orange stars, yellow (like our sun), white, and blue, in order of increasing hotness. (If you are wondering why we do not see stars in such vivid colors with our naked eyes, that has to do with the fact that only our color-insensitive rod cells of the retina are activated by the dim light of the stars.)

Question: Why don't we see any green stars?

Answer: Green, as you know, has a frequency right in the middle of the visible spectrum. So when green is prominent, so are the other frequencies on both sides, and the color would be white.

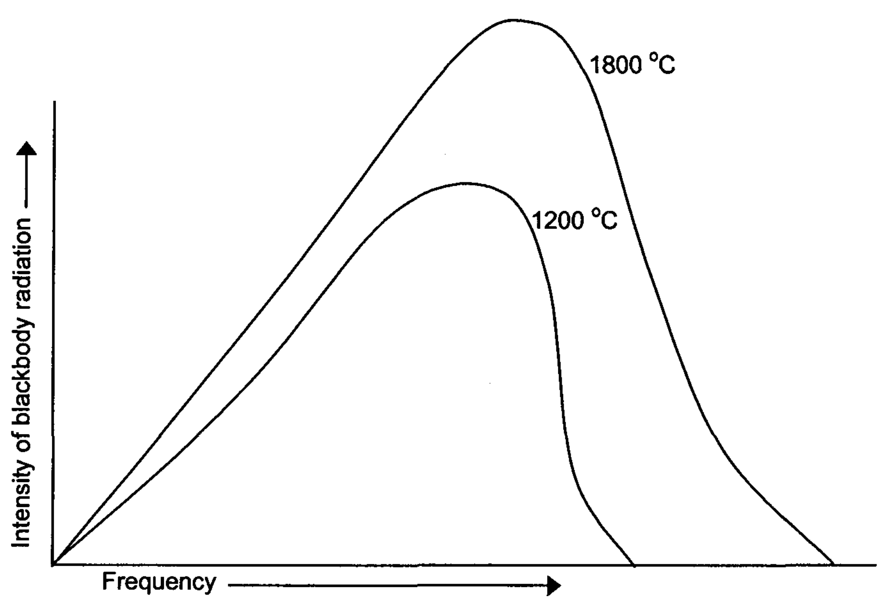

Figure 3.2
At a higher temperature the intensity is much greater than at a lower temperature. Also, the spectrum (and the maximum) shifts toward higher frequency at a higher temperature.

The classical physics model that people in Planck's time developed for blackbody radiation is based in part on *thermodynamics*, the science of interchange of heat and other forms of energy. There was also *Maxwell's electromagnetic theory*, another milestone of classical physics, to guide them. Maxwell's theory tells us that radiation must be due to the jiggling motion of a few charges among the atoms of the body. Ultimately, the charges can be identified as the electrons, but there are so many interactions that we can forget about the individual electrons and assume that the radiation is due to a few charged oscillators, ignoring the detailed character of the oscillators.

Now these oscillators move up and down and radiate and ordinarily lose energy and cool down. But if we keep them in a closed box with perfectly reflecting walls, the oscillators can keep on moving. They lose energy by radiation, no doubt, but some of the radiation comes back and returns the energy to the oscillator. Thus we can achieve a state of thermal equilibrium (no net one-way flow of energy) between the oscillators and the confined radiation. The average energy of such an oscillator is the same regardless of the wavelength of the radiation it emits; the average energy is just proportional to the absolute temperature. (*Absolute temperature* is temperature measured on the absolute temperature scale; if you add 273 to the Celsius temperature of an object, you get its absolute temperature.) All this is according to the classical physics known at the turn of the century.

Unfortunately, the number of oscillators of a given frequency increases rapidly with the frequency. And this means trouble. So one result of the classical thermodynamic theory above is that most of the energy inside the black box will be in the form of high-frequency radiation—ultraviolet and so forth. Of course, this is just not true if we review the experimental data of Figure 3.1. According to experiments, for any given temperature only a finite amount of energy is contained in the high-frequency portion of the spectrum. If the thermodynamic theory were correct, we would get sunburns from ultraviolet radiation every time we had a fire going in a fireplace.

What is more catastrophic is that in even a small part of the space inside the black enclosure, the total energy would be infinite, according to arguments as above, because of the contribution of the high-frequency oscillators to the total energy. So if the thermodynamic theory of radiation was the final truth, energy would just drain out of matter and go into radiation and everything would become absolutely cold. We all know that this does not happen. So what is wrong with this theory?

The Energy Quanta of Max Planck

Once in Soviet Russia a professor wrote down the equation

$$E = h\nu$$

and asked one of his students, "What is ν?" "Planck's constant," the student answered. Taken aback, the professor asked, "Then what is h?" "The length of the plank," the student answered unabashedly.

The student was slightly mistaken, as you no doubt suspect since in physics, the symbol ν almost always denotes frequency and it is not hard to figure out that E denotes energy. So the only unknown is h. But then, if you knew the name Planck, you would know of h; h is a fundamental constant of nature known as *Planck's constant*. The equation $E = h\nu$, introduced by Max Planck, was the first (but not the last) appearance of this constant h in our picture of the world. The entire quantum revolution can be traced to the potential power of this one mathematical equation.

What is so phenomenal about this equation? Before Planck's theory, energy had always been regarded as a continuous variable. Energy was assumed to be emitted or absorbed in as small a dosage as you can imagine, all the way down to zero. But Planck's equation says otherwise. For each frequency of the radiation emitted, the size of the energy bundle is h times the frequency: no more, no less. Energy can be exchanged from the system only in multiples of these bundles, or *quanta*. Energy is quantized. It is like having a minimum currency: we cannot exchange coins in any denomination less than a cent; all exchanges must occur in integer multiples of cents.

The constant h has the same units as the product of energy and time, or what physicists refer to as action. So h is often referred to as the quantum of action. The unit of h is the product of a unit of energy, which is a joule, and a unit of time, which is a second. Its value has been established from very careful experimentation to be

$$h = 6.62 \times 10^{-34} \text{ joule-second.}$$

As you can see, h is a very small number. This is the reason that the quantum nature of things does not play much of a role in the behavior of the macroworld, that is, in the motion of large objects.

Obviously, the classical theory needs some way to avoid the high-frequency catastrophe, some way to suppress the contribution to the total energy coming from the high-frequency components of the radiation spectrum. Since the number of oscillators increases rapidly with frequency, if the average energy of oscillators somehow decreased rapidly with frequency also, then the product of the two could be finite. This is what Planck was able to show with his $E = h\nu$. That, and the quantum jump.

Planck's sparkle of new insight into the problem was the realization that the charged oscillators of a blackbody can only absorb energy in quantum jumps, $h\nu$ at a time. The oscillators exist in states of quantized energy resembling a staircase: the steps of the staircase are called *energy levels* (Figure 3.3). This analogy is really a very good one. If you are walking on a ramp, your potential energy changes continuously, according to the classical assumption. But if you imagine yourself on a stair-case, your potential energy in earth's gravity field can change only by discrete steps, quantum jumps; the difference, of course, is that in everyday life we can build the staircase with steps of varying length. Nature, on the other hand, has a fixed length for its quantum jump, a length determined by h. This, in fact, is the significance of the quantum of action h.

So now we can imagine the following picture. For each frequency ν there are a lot of oscillators whose steps have the length $h\nu$. Many of them will be at the ground level, taking no energy at all. A few others will absorb one quantum of radiation and will move to the first excited state, but the number of these is much smaller than the number in their

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