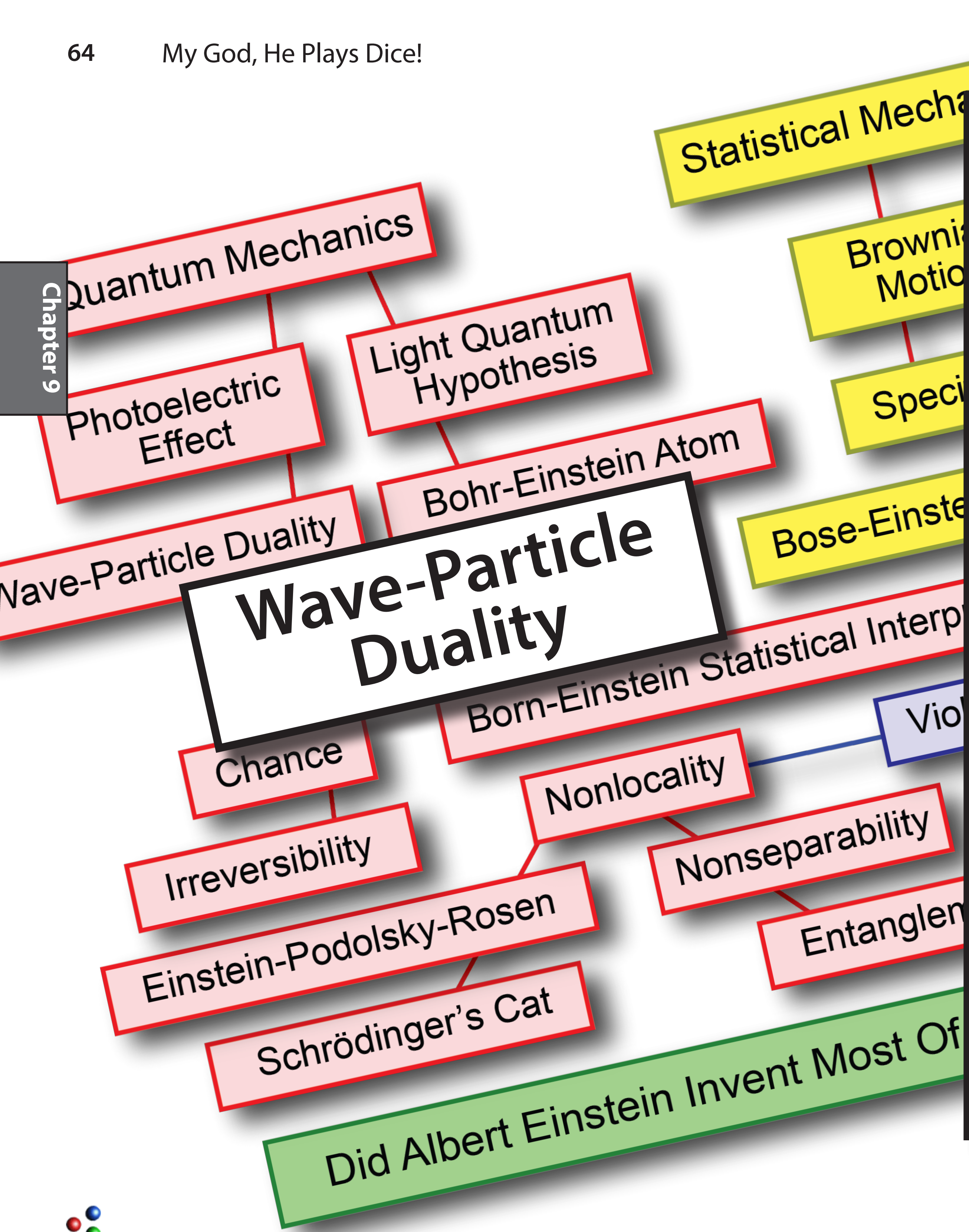

Wave-Particle Duality

Einstein greatly expanded his light-quantum hypothesis in his presentation at the Salzburg conference in September, 1909. He argued that the interaction of radiation and matter involves elementary processes that have no inverse, a deep insight into the *irreversibility* of natural processes. While incoming spherical waves of radiation are mathematically possible, they are not practically achievable. Nature appears to be asymmetric in time. Einstein speculates that the continuous electromagnetic field might be made up of large numbers of light quanta - singular points in a field that superimpose collectively to create the wavelike behavior.

Although Einstein could not yet formulate a mathematical theory that does justice to both the *continuous* oscillatory and *discrete* quantum structures - the wave and particle pictures, he argued that they are compatible. This was more than fifteen years before Werner Heisenberg's particle matrix mechanics and Erwin Schrödinger's wave mechanics in the 1920's. Because gases behave statistically, Einstein thought that the connection between waves and particles may involve probabilistic behavior.

> Once it had been recognized that light exhibits the phenomena of interference and diffraction, it seemed hardly doubtful any longer that light is to be conceived as a wave motion. Since light can also propagate through vacuum, one had to imagine that vacuum, too, contains some special kind of matter that mediates the propagation of light waves. [the ether] However, today we must regard the ether hypothesis as an obsolete standpoint. It is even undeniable that there is an extensive group of facts concerning radiation that shows that light possesses certain fundamental properties that can be understood far more readily from the standpoint of Newton's emission theory of light than from the standpoint of the wave theory. [1]

Einstein's 1905 relativity theory requires that the inertial mass of an object decreases by L/c^2 when that object emits radiation

1 CPAE, vol.2. p. 379

of energy L. The inertial mass of an object is diminished by the emission of light. Einstein now says in 1909,

> The energy given up was part of the mass of the object. One can further conclude that every absorption or release of energy brings with it an increase or decrease in the mass of the object under consideration. Energy and mass seem to be just as equivalent as heat and mechanical energy.

Indeed, in 1905, Einstein had shown that $E = mc^2$. He had found a *symmetry* between light and matter. They are both particles. But in 1909 Eintsein finds the wave nature of light emerging from his equations and suggests a "fusion" of wave and particle theories

> It is therefore my opinion that the next stage in the development of theoretical physics will bring us a theory of light that can be understood as a kind of fusion of the wave and emission theories of light. To give reasons for this opinion and to show that a profound change in our views on the nature and constitution of light is imperative is the purpose of the following remarks.[2]

On the other hand, Einstein identified an important *asymmetry*.

> In the kinetic theory of molecules, for every process in which only a few elementary particles participate (e.g., molecular collisions), the inverse process also exists. But that is not the case for the elementary processes of radiation. In the foregoing it has been assumed that the energy of at least some of the quanta of the incident light is delivered completely to individual electrons.
>
> According to our prevailing theory, an oscillating ion generates a spherical wave that propagates outwards. The inverse process does not exist as an elementary process. A converging spherical wave is mathematically possible, to be sure; but to approach its realization requires a vast number of emitting entities. The elementary process of emission is not invertible. In this, I believe, our oscillation theory does not hit the mark. Newton's emission theory of light seems to contain more truth with respect to this point than the oscillation theory since, first of all, the energy given to a light particle is not scattered over infinite space, but remains available for an elementary process of absorption.[3]

Recall from chapter 4 that Planck had argued the interaction of light with matter might explain the *irreversibility* of the increase in

2 *ibid.*, p.379

3 *ibid.*, p.387

entropy of the second law of thermodynamics. Planck thought a plane wave might be converted to a spherical wave going outward from the oscillator. But Boltzmann had talked him out of the idea, because time reversal would produce the incoming wave that Einstein here says is impossible. We shall see that Einstein's insight can explain the origin of *microscopic irreversibility*. See chapter 12.

From Matter to Light to Matter

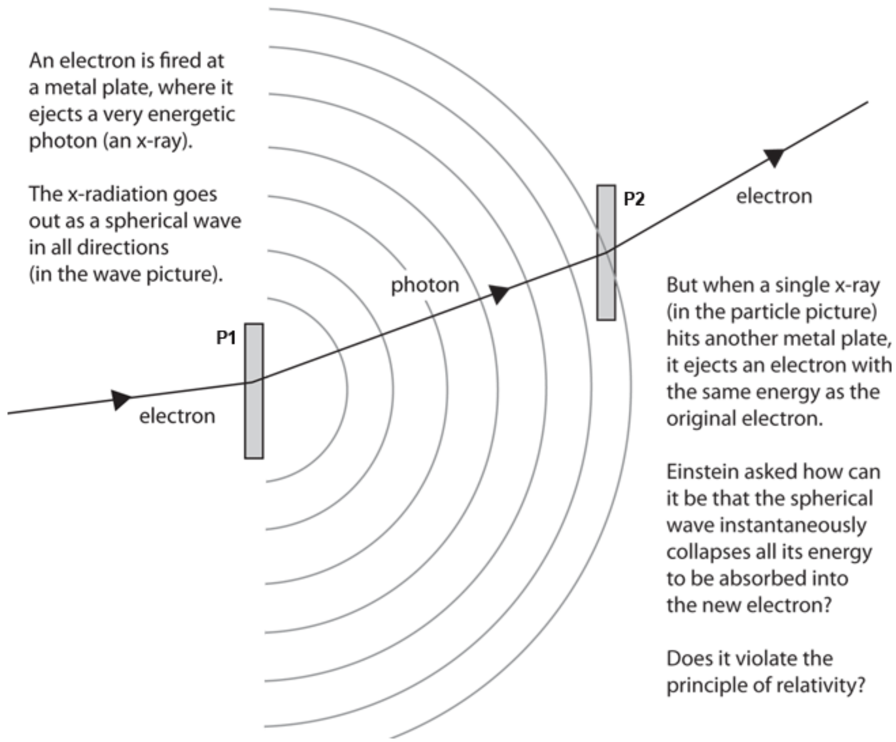

Figure 9-9. Einstein's picture of waves and particles.

Einstein imagined an experiment in which the energy of an electron (a cathode ray) is converted to a light quantum and back.

> Consider the laws governing the production of secondary cathode radiation by X-rays. If primary cathode rays impinge on a metal plate P1, they produce X-rays. If these X-rays impinge on a second metal plate P2, cathode rays are again produced whose speed is of the same order as that of the primary cathode rays.

> As far as we know today, the speed of the secondary cathode rays depends neither on the distance between P1 and P2, nor on the intensity of the primary cathode rays, but rather entirely on the speed of the primary cathode rays. Let's assume that this is strictly true. What would happen if we reduced the intensity of the primary cathode rays or the size of P1 on which they fall, so that the impact of an electron of the primary cathode rays can be considered an isolated process?
>
> If the above is really true then, because of the independence of the secondary cathode rays' speed on the primary cathode rays' intensity, we must assume that an electron impinging on P1 will either cause no electrons to be produced at P2, or else a secondary emission of an electron whose speed is of the same order as that of the initial electron impinging on P1. In other words, the elementary process of radiation seems to occur in such a way that it does not scatter the energy of the primary electron in a spherical wave propagating in every direction, as the oscillation theory demands.[4]

Extending his 1905 hypothesis, Einstein shows energy can not spread out like a wave continuously over a large volume, because it is absorbed in its entirety to produce an ejected electron at P2, with essentially the same energy as the original electron absorbed at P1.

> Rather, at least a large part of this energy seems to be available at some place on P2, or somewhere else. The elementary process of the emission of radiation appears to be directional. Moreover, one has the impression that the production of X-rays at P1 and the production of secondary cathode rays at P2 are essentially inverse processes...Therefore, the constitution of radiation seems to be different from what our oscillation theory predicts.
>
> The theory of thermal radiation has given important clues about this, mostly by the theory on which Planck based his radiation formula...Planck's theory leads to the following conjecture. If it is really true that a radiative resonator can only assume energy values that are multiples of *hv*, the obvious assumption is that the emission and absorption of light occurs only in these energy quantities.[5]

4 *ibid.*, p.387

5 *ibid*,, p.390

This important conjecture by Einstein, that light is emitted and absorbed in units of *hν*, is often misattributed to Max Planck, who never fully accepted Einstein's "very revolutionary" hypothesis..

Einstein found theoretical evidence for his "fusion of wave and emission theories of light" in his study of statistical fluctuations of the gas pressure (collisions with gas particles) and the radiation pressure (collisons with light quanta) on a metal plate suspended in a cavity.

Using results from his years deriving the laws of statistical mechanics, and assuming the plate, the cavity walls, the gas and the light particles are all in equilibrium at temperature *T*, he derived an expression for the fluctuations in the radiation pressure in the frequency interval *dν* as containing two terms.

$$<\varepsilon^2> = (V d\nu)\, \{h\nu\rho + (c^3/8\pi\nu^2)\, \rho^2\}.$$

> The wave theory provides an explanation only for the second term... That the expression for this fluctuation must have the form of the second term of our formula can be seen by a simple dimensional analysis.
>
> But how to explain the first term of the formula?... If radiation consisted of very small-sized complexes of energy *hν*,... a conception that represents the very roughest visualization of the hypothesis of light quanta—then the momenta acting on our plate due to fluctuations of the radiation pressure would be of the kind represented by the first term alone.[6]

In a second independent analysis using Boltzmann's principle to calculate the mean squared energy fluctuation in terms of the density of radiation ρ with frequency *ν*, and substituting Planck's radiation law for *ρ (ν)*, Einstein once again derived the two-term expression for fluctuations in the radiation pressure.[7]

Einstein can again see the first (particle) term with light quanta *hν* and the second (wave) term with the classical expression for the number of modes $8\pi\nu^2/c^3$ in the radiation field with frequency *ν*. The first term describes light with high frequencies (Wien's Law), the second light with long wavelengths (Rayleigh-Jeans Law).

6 *ibid*,, p.393

7 See Klein, 1964, p.11