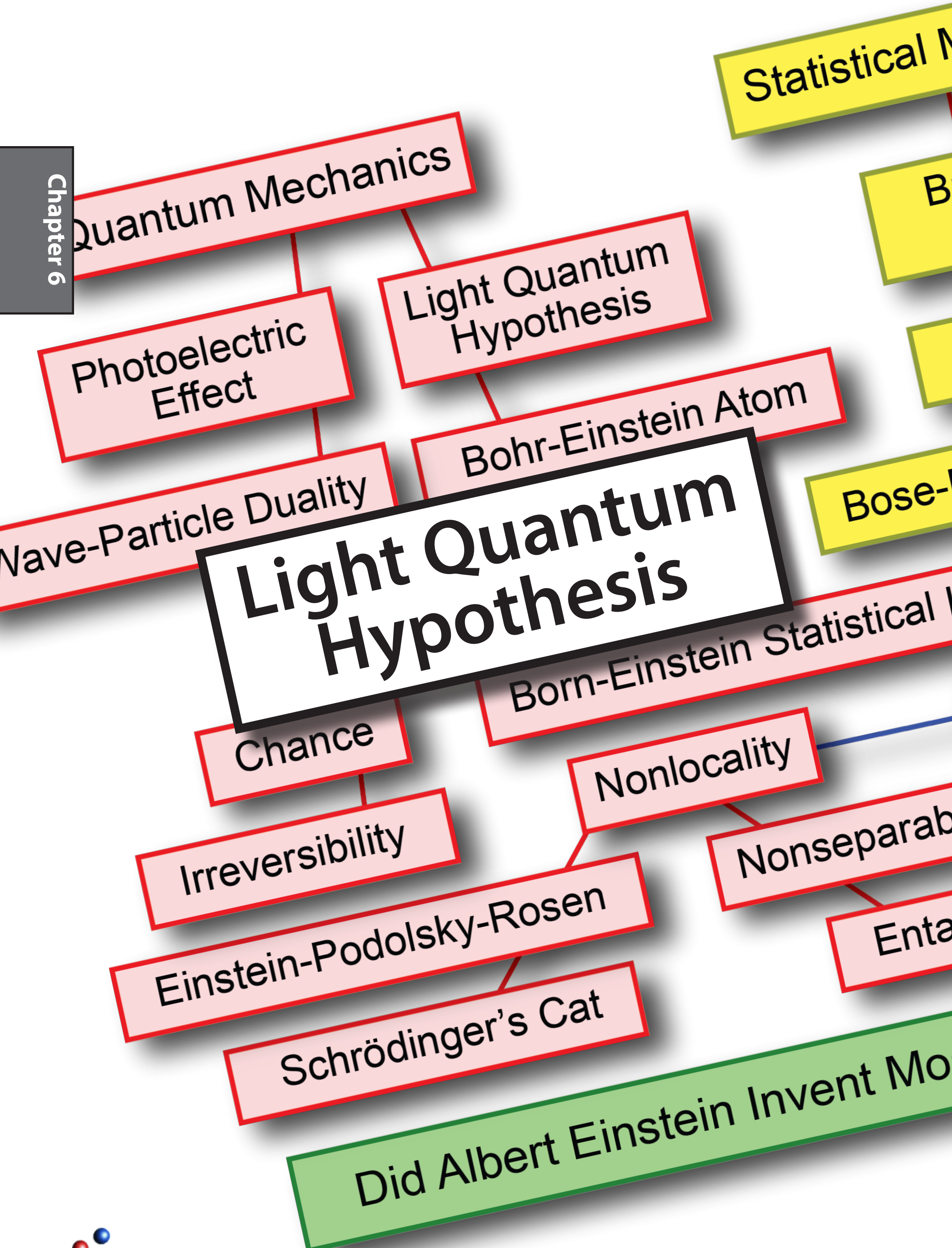
Statistical
Quantum Mechanics
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Light Quantum Hypothesis

In his "miracle year" of 1905, Einstein wrote four extraordinary papers, one of which won him the 1921 Nobel prize in physics. Surprisingly, the prize was not for his third paper, on the theory of relativity. Special relativity was accepted widely, but it remained controversial for some conservative physicists on the Nobel committee. Nor was it for the second paper, in which Einstein showed how to prove the existence of material particles. Nor even the fourth, in which the famous equation $E = mc^2$ first appeared.

Einstein's Nobel Prize was for the first paper of 1905. In it he hypothesized the existence of light particles. The prize was not for this hypothesis he called "very revolutionary." The prize was for his explanation for the photoelectric effect (as quanta of light!).

The idea that light consists of discrete "quanta," which today we call *photons*, was indeed so revolutionary that it was not accepted by most physicists for *nearly two decades*, and then reluctantly, because it leaves us with the mysterious dual aspect of light as sometimes a particle, and sometimes a wave.

A close reading of Einstein's work will give us the tools to resolve this quantum mystery and several others. But we begin with trying to see today what Einstein already saw clearly in 1905.

We must keep in mind that the model of a physical theory for Einstein was a "field theory." A field is a *continuous* function of four-dimensional space-time variables such as Newton's gravitational field and Maxwell's electrodynamics.

For Einstein, the theories and principles of physics are *fictions* and "free creations of the human mind." Although they must be tested by experiment, one cannot *derive* the basic laws from experience, he said. And this is particularly true of field theories, like his dream of a "unified field theory." They are thought to have continuous values at every point in otherwise empty space and time. Listen to Einstein's concern in his first sentence of 1905...

> There exists a profound formal distinction between the theoretical concepts which physicists have formed regarding gases and other ponderable bodies and the Maxwellian theory of electromagnetic processes in so-called empty space. [1]

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1 "The Production and Transformation of Light from a Heuristic Viewpoint," *Collected Papers of Albert Einstein*, Doc. 14. p.86

> According to the Maxwellian theory, energy is to be considered a continuous spatial function in the case of all purely electromagnetic phenomena including light, while the energy of a ponderable object should, according to the present conceptions of physicists, be represented as a sum carried over the atoms and electrons...[2]

Here Einstein first raises the deep question that we hope to show he struggled with his entire life. *Is nature continuous or discrete?*

Is it possible that the physical world is made up of nothing but discrete discontinuous *particles*? Are continuous *fields* with well-defined values for matter and energy at all places and times simply *fictional* constructs, *averages* over large numbers of particles?

> The energy of a ponderable body cannot be subdivided into arbitrarily many or arbitrarily small parts, while the energy of a beam of light from a point source (according to the Maxwellian theory of light or, more generally, according to any wave theory) is continuously spread over an ever increasing volume.
>
> It should be kept in mind, however, that the optical observations refer to time averages rather than instantaneous values. In spite of the complete experimental confirmation of the theory as applied to diffraction, reflection, refraction, dispersion, etc., it is still conceivable that the theory of light which operates with continuous spatial functions may lead to contradictions with experience when it is applied to the phenomena of emission and transformation of light.[3]

One should keep in mind, Einstein says, that our observations apply to averages (over a finite number of particles) and that a continuum theory leads to contradictions with emission and absorption processes. In particular, the continuum has an infinite number of "degrees of freedom," while matter and energy quanta are finite. We saw in chapter 3 that Ludwig Boltzmann had made this point,

> "An actual continuum must consist of an infinite number of parts; but an infinite number is undefinable... Thus the mechanical foundations of the partial differential equations, when based on the coming and going of smaller particles, with restricted average values, gain greatly in plausibility."[4]

2 CPAE, Doc. 14. p.86
3 CPAE, Doc. 14. p.86-87
4 *Lectures on Gas Theory, §1, p.27*

The Photoelectric Effect

Continuing his investigations into a single theory that would describe both matter and radiation, Einstein proposed his “very revolutionary” hypothesis to explain a new experiment that showed a direct connection between radiation and electrons.

Before Einstein, it was thought that the oscillations of electrons in a metal are responsible for the emission of electromagnetic waves, but Einstein argued that it is the *absorption* of light that is causing the ejection of electrons from various metal surfaces.

It is called the *photoelectric effect*.

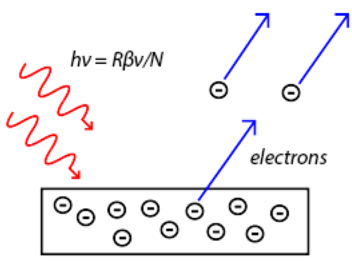
Heinrich Hertz had shown in 1889 that high-voltage spark gaps emit electromagnetic waves that are light waves obeying Maxwell’s equations. He also noticed that ultraviolet light shining on his spark gaps helped them to spark. In 1902, the Hungarian physicist Philipp Lenard confirmed that light waves of sufficiently high frequency v shining on a metal surface cause it to eject electrons.

To Lenard’s surprise, below a certain frequency, no electrons are ejected no matter how strong he made the intensity of the light. Assuming that the energy in the light wave was simply being converted into the energy of moving electrons, this made no sense.

Furthermore, when Lenard increased the frequency of the incident light (above a critical frequency v_c) the ejected electrons appeared to move faster for higher light frequencies.

These strange behaviors gave Einstein very strong reasons for imagining that light must be concentrated in a physically localized bundle of energy. He wrote:

> The usual conception, that the energy of light is continuously distributed over the space through which it propagates, encounters very serious difficulties when one attempts to explain the photoelectric phenomena, as has been pointed out in Herr Lenard’s pioneering paper.



> According to the concept that the incident light consists of energy quanta of magnitude Rβν/N [*hν*],

> however, one can conceive of the ejection of electrons by light in the following way. Energy quanta penetrate into the surface layer of the body, and their energy is transformed, at least in part, into kinetic energy of electrons. The simplest way to imagine this is that a light quantum delivers its entire energy to a single electron; we shall assume that this is what happens...
>
> An electron to which kinetic energy has been imparted in the interior of the body will have lost some of this energy by the time it reaches the surface. Furthermore, we shall assume that in leaving the body each electron must perform an amount of work P characteristic of the substance...
>
> If each energy quantum of the incident light, independently of everything else, delivers its energy to electrons, then the velocity distribution of the ejected electrons will be independent of the intensity of the incident light; on the other hand the number of electrons leaving the body will, if other conditions are kept constant, be proportional to the intensity of the incident light... [5]

Einstein shows here that the whole energy of an incident light quantum is absorbed by a single electron.

Some of the energy absorbed by the electron becomes *P*, the work needed to escape from the metal. The rest is the kinetic energy E = ½ mv^2 of the electron. Einstein's "photoelectric equation" thus is

$E = hv - P.$

Einstein's equation predicted a linear relationship between the frequency of Einstein's light quantum *hv*, and the energy *E* of the ejected electron. It was more than ten years later that R. A. Millikan confirmed Einstein's photoelectric equation. Millikan nevertheless denied that his experiment proved Einstein's radical but clairvoyant ideas about light quanta! He said in 1916

> Einstein's photoelectric equation... cannot in my judgment be looked upon at present as resting upon any sort of a satisfactory theoretical foundation. [6]

5 CPAE, vol.2, Doc. 14, p.99.
6 A Direct Photoelectric Determination of Planck's "h". *Physical Review*, 7(3), 355.

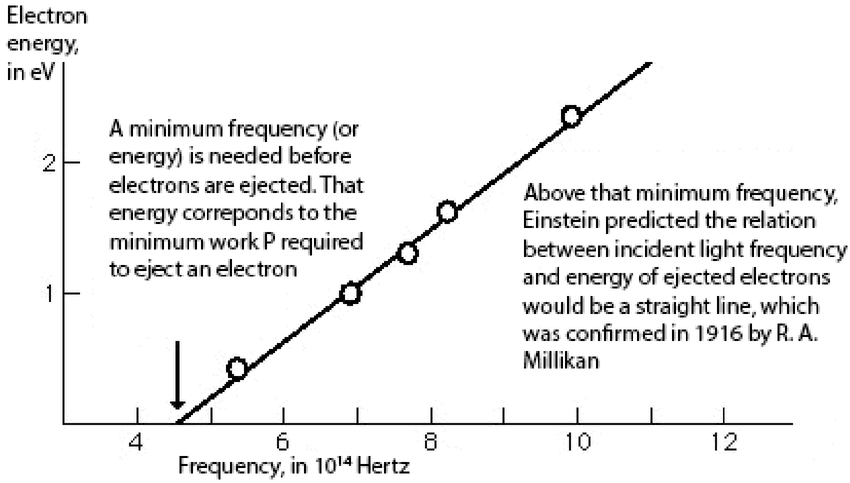


Figure 6-7. The Photoelectric Effect.

The Entropies of Radiation and Matter

Einstein clearly recognized the well-established difference between matter and energy, but he hoped to find some kind of symmetry between them in a general theory that describes them both.

Within the 1905 year, he writes the most famous equation in physics that connects the two, $E = mc^2$. But Einstein discovers a symmetry by calculating the entropy of matter and radiation, using the methods he developed in his three papers on statistical mechanics.[7]

Einstein begins by asking for the probability W that a particular movable point (an abstract property of a molecule) would be randomly found in a small volume v in a large container with volume v_0. He then asks "how great is the probability that at a randomly chosen instant of time all n independently movable points in a given volume v_0 will be contained (by chance) in volume v?"

The probability of independent events is the product of the individual probabilities, so $W = [v/\ v_0]^n$. Einstein then uses "Boltzmann's Principle, that the entropy $S = k\ log\ W$.

$S - S_0 = k \log [v/\ v_0]^n = k\, n \log [v/\ v_0]$

Einstein derived a similar expression for the entropy of radiation with energy E and frequency ν as

7 See chapter 5.

$S - S_0 = k\ (E/h\nu) \log [\nu/ \nu_0]$

If we compare the two expressions, it appears that $E/h\nu$ is the *number* of independent light particles. Einstein concluded

> Monochromatic radiation of low density (within the range of validity of Wien's radiation formula) behaves thermodynamically as if it consisted of mutually independent energy quanta of magnitude $h\nu$ [Einstein wrote $R\beta\nu/N$]. [8]

Einstein showed that thermodynamically, radiation behaves like gas particles. It seems reasonable, he said,

> "to investigate whether the laws of generation and conversion of light are also so constituted as if light consisted of such energy quanta. Light can not be spread out continuously in all directions if individual energy quanta can be absorbed as a unit that ejects a photoelectron in the photoelectric effect."

Nonlocality

How can energy spread out continuously over a large volume yet later be absorbed in its entirety at one place, without contradicting his principle of relativity? Einstein clearly describes here what is today known as *nonlocality*, but he does not describe it explicitly until 1927, and then only in comments at the fifth Solvay conference. He does not publish his concerns until the EPR paper in 1935!

If the energy travels as a spherical light wave radiated into space in all directions, how can it instantaneously collect itself together to be absorbed into a single electron. Einstein already in 1905 sees something *nonlocal* about the photon. What is it that Einstein sees?

It is events at two points in a spacelike separation occurring "simultaneously," a concept that his new special theory of relativity says is impossible in any absolute sense.

He also sees that there is both a wave aspect and a particle aspect to electromagnetic radiation. He strongly contrasts the finite number of variables that describe *discrete* matter with the assumption of *continuous* radiation.

> While we consider the state of a body to be completely determined by the positions and velocities of a very large, yet finite, number of

8 CPAE, vol2. Doc.14, p.97.

atoms and electrons, we make use of continuous spatial functions to describe the electromagnetic state of a given volume, and a finite number of parameters cannot be regarded as sufficient for the complete determination of such a state.

The wave theory of light, which operates with continuous spatial functions, has worked well in the representation of purely optical phenomena and will probably never be replaced by another theory.

It seems to me that the observations associated with blackbody radiation, fluorescence, the production of cathode rays by ultraviolet light, and other related phenomena connected with the emission or transformation of light are more readily understood if one assumes that the energy of light is discontinuously distributed in space.

In accordance with the assumption to be considered here, the energy of a light ray spreading out from a point source is not continuously distributed over an increasing space but consists of a finite number of energy quanta which are localized at points in space, which move without dividing, and which can only be produced and absorbed as complete units.

We therefore arrive at the conclusion: the greater the energy density and the wavelength of a radiation, the more useful do the theoretical principles we have employed turn out to be; for small wavelengths and small radiation densities, however, these principles fail us completely. [9]

As late as the Spring of 1926, perhaps following Niels Bohr, Werner Heisenberg could not believe in the reality of light quanta.

Whether or not I should believe in light quanta, I cannot say at this stage. Radiation quite obviously involves the discontinuous elements to which you refer as light quanta. On the other hand, there is a continuous element, which appears, for instance, in interference phenomena, and which is much more simply described by the wave theory of light. But you are of course quite right to ask whether quantum mechanics has anything new to say on these terribly difficult problems. I believe that we may at least hope that it will one day. [10]

9 CPAE, vol.2, Document 14,

10 *Physics and Beyond*, p. 67