

Modern Physics (PHY 3305) Lecture Notes

Radiation as Particles (Ch. 3.1-3.5)

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Review

no tags

Today

- We will begin a discussion of radiation and the "blackbody problem" that kicked off the quantum revolution
- We will explore the "photoelectric effect", which helped to seal the fate of our classical understanding of radiation and light
- We will discuss other evidence for the particle properties of radiation and bring the discussion of light full circle

Another Consequence of Einstein's *Energy-Momentum-Mass* Revelation

Let's discuss one more of the consequences of the innocuous-looking equation, $E^2 = (mc^2)^2 + (pc)^2$:

- What happens when the mass of an object is zero? Is that even allowed?
 - When mass is zero, $E = pc$. It seems that there is no prior reason to believe such a thing cannot exist; the equation allows it, but what does the equation mean about such an object? If you write this as $E = \gamma_u mu$, the ONLY way that the energy of such an object can be anything but zero is if $u = c$ so that $\gamma_u = \infty$. While relativity fails to tell you about the properties of this object (e.g. exactly what its energy is!), it doesn't rule out that such objects can exist and if they do they must move at the speed of light. What moves at the speed of light? Light. Light is a massless particle, but we won't learn much more about it from relativity since it's undefinable in relativity.

Relativity has little more to say right now regarding massless things that

move at the speed of light. Let's move forward.

Basic Questions

- WHAT IS A WAVE?
- WHAT IS A PARTICLE?

Parallel Revolution: The Quantization of Energy

In parallel with the realizations of Lorentz, Einstein, and others regarding the nature of space and time were developments in energy and matter. These developments were initiated by Max Planck and his studies of the so-called "blackbody problem." His hypothesis, which resolved this problem, had stunning implications for the nature of energy and, in turn, matter. We will discuss today the "blackbody problem" and its resolution. We will then begin exploring the implications of this solution, and the experimental evidence that confirmed those implications.

Blackbody Radiation

A *blackbody* is defined as follows:

- A *blackbody* is any object whose emitted electromagnetic radiation results solely from thermal motion of its electric charges.

The name then becomes clear; we only see things because light scatters off of it and strikes our eyes. If no light can scatter (be emitted from) an object, then it appears black to us. However, this is only one class of such object. Name some common blackbodies in nature.

- Common blackbodies:
 - coal (tar, oil, etc.) or anything painted black
 - an oven
 - the sun
 - the cosmic microwave background

A quantity of interest experimentally when dealing with blackbodies is the

amount of energy radiated per unit radiation frequency, or the *spectral energy density*. This is written as dU/df .

Consider the following blackbody. A cavity is constructed such that the entire volume is enclosed except for a pin-sized hole on one wall. Radiation can enter the cavity through this hole, but once inside the probability of it reflecting off the walls and escaping is small. Thus, incident radiation primarily goes into heating the interior walls of the cavity. Such an object is a blackbody; light entering the hole is converted to heat in the cavity walls, and little or no light escapes. Therefore, the cavity is an excellent blackbody, and was a favorite construct for 19th-century blackbody studies.

Now, classical physics lets us calculate the spectral energy density of this blackbody. It's a very details calculation (c.f. Eisberg and Resnick, Chapter 1-3: "Classical Theory of Cavity Radiation". The summary of the calculation is as follows. You can think of the radiation trapped in the cavity as sinusoidal waves resonating in the cavity, with arbitrary amplitudes. Classical Thermodynamics tells us that the average energy of any wave of a given frequency f is $k_B T$, where k_B is *Boltzmann's Constant*:

- $k_B = 1.380... \times 10^{-23} J/K$

and T is the temperature of the cavity. If we then multiply this average energy by the number of waves for a given range of frequency, df , in the cavity volume V , we arrive at the classical prediction:

$$\frac{dU}{df} = k_B T \times \frac{8\pi V}{c^3} f^2$$

How did this compare to experimental observation of such cavities? Poorly! This function DIVERGES as the frequency increases, meaning that if the waves in the cavity have high frequencies their energy diverges as the square of the frequency. This is the so-called "Ultraviolet Catastrophe" - high-frequency radiation (ultraviolet) present in the cavity would have huge amounts of energy. Data, instead, said the energy spectral density peaked at a value and then fell off for high-frequency radiation: