The ultraviolet myth

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Outline

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Electrons in circular orbits should radiate

Larmor points this out in 1897, two months after Thomson discovered the electron and Nagaoka, in his article about his saturnian atomic model in 1904, says,

> *The objection to such a system of electrons is that the system must ultimately come to rest, in consequence of the exhaustion of energy radiation, if the loss be not properly compensated. — Nagaoka, 1904*

Thomson

Thomson tried to use this; maybe it is the mechanism behind radioactive decay?!

But he also showed that for large numbers of electrons, the radiation is highly suppressed; for 6 electrons going 1% of c, it is only 1.6×10^{-17} of that from one electron.

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A (unsolvable?) problem for everyone

Textbooks claim the problem came with Rutherford discovering the nucleus. This is not true!
All models had electrons in circles, only Rutherford did not talk about the electrons.

How can you not have electrons in circular orbits in the atom?
It seems physicists are pragmatic. We work, not on the biggest problems, but on those where we think progress is possible.

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Radiative stability did not concern Bohr

Bohr wanted to calculate the ground state of the atom, he then noticed that introducing quantization gave him Balmer's formula.

He does point out that radiative stability is a problem for hydrogen because it only has one electron, but that is an argument for his model after it is constructed, not a motivation before hand.

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The standard story

We are told that classical physics predict for blackbodies,

$$I(f) \propto f^2.$$

Where does this come from?
Turns out this is called the Rayleigh-Jeans-Einstein radiation law and all three of them talked about it in 1905. The term Ultraviolet catastrophe came in 1911, but Einstein used the arguments in his light quanta paper in 1905.

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Rayleigh 1900

Rayleigh writes about the equipartition principle,

> *According to this doctrine every mode of vibration should be alike favoured, and although for some reason not yet explained the doctrine fails in general, it seems possible that it may apply to the graver modes.*

He then derives the result and says,

> *If we introduce the exponential factor, the complete expression will be,*

and he gives the result which in modern notation would be,

$$I(f, T) = c_1 T f^2 e^{-\frac{c_2 f}{T}}, \tag{1}$$

where c_1 and c_2 are constants.

The equipartition principle and heat capacity

What is the molar heat capacity at constant volume for an ideal gas?

$$C_V = \frac{n_{dof}}{2} R. \quad (2)$$

But what is n_{dof} for an diatomic gas? 5 or 7? or 8?
Experiments said 5 but why? and why is it so small for more complex molecules?
And it depends on temperature???

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Blackbodies

Kirchhof proved that the spectrum from a blackbody can only depend on temperature and frequency. He then argued that it is very important to find this function, that probably is rather simple.

Then came Stefan-Boltzmann: $I = \sigma T^4$,
And Wien: $\lambda_{max} T = konst$.
Finally Wien gave a radiation law that seemed to work,

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Enter Planck

We have a law,

$$I(f,T) = \alpha f^3 e^{-\frac{\beta f}{T}}, \quad (4)$$

but why this law? Planck wanted to derive it.

He stated that the entropy of atomic oscillators is,

$$S = -\frac{U_f}{af}\ln\frac{U_f}{ebf}. \quad (5)$$

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Better experiments

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He had derived what he thought to be the right radiation law from an entropy expression with reasonable mathematical properties and no sign of probability.

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The road to Planck's radiation law

Planck had experimentalist friends who told him about the new data and he acted quickly.
By modifying his entropy expression he managed to derive a new radiation law,

$$I(\lambda, T) = \frac{C\lambda^{-5}}{e^{\frac{c}{\lambda T}} - 1}, \tag{6}$$

which in modern notation and normalized and as a function of frequency looks like,

$$I(f, T) = \frac{8\pi h f^3}{c^3} \frac{1}{e^{\frac{hf}{kT}} - 1}. \tag{7}$$

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Deriving the law

Planck had derived his law from a rather ad-hoc entropy expression, he wanted to do better.
The only way he found was to deploy the (by him) dreaded statistical mechanics of Boltzmann and use on the oscillators that emit radiation. To do statistics he needed finite possibilities so he divided the energy into chunks of hf.

- Planck himself saw the "quantization" as merely a mathematical artefact
- He "quantized" the energy of the oscillators, not the radiation
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Quantizing energy

The revolutionary “quantization” did not draw any attention, not even from Planck himself.

It is Einstein who picks up on it and shows that this demonstrates something new and remarkable, in doing so he derives the UV-divergent classical law.

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Why should we care?

- It is rather embarrassing for a meticulous field like physics.
- The real story is often more interesting, and can teach us more about physics and scientific progress.
- These myths are not simplifications!

Referanser

In Norwegian: “Innføring i Fysikk” by Reidun and Therese Renstrøm.
Books and articles by **Helge Kragh** especially; “Max Planck: the reluctant revolutionary”, *Phys. World **13** (2000), (12), 31.*

Planck’s work:

“On an Improvement of Wiens Equation for the Spectrum”, *Verhandl. Dtsch. phys. Ges., **2** (1900), 202*

“On the Theory of the Energy Distribution Law of the Normal Spectrum”, *Verhandl. Dtsch. phys. Ges., **2** (1900), 237*

Abraham Pais:

Subtle is the lord, Oxford university press (1982)

Inward bound, Clarendon Press (1986)

Norsk Fysisk Selskap has a network in history of physics that hopefully will get more active.