Teacher notes
Topic E

Oppenheimer

No, this is not a review of Christopher Nolan's movie!

The movie may have made Oppenheimer a household name so now everybody knows him as the director of the Manhattan project that led to the American nuclear fission bomb, but what did Oppenheimer do in Physics?

J. R. Oppenheimer

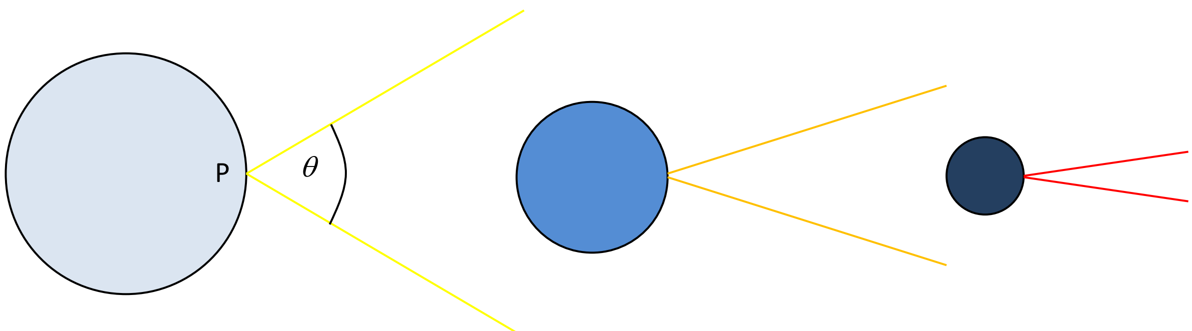
Well, he did a hell of a lot!

In 1926, still 22 years of age and a graduate student, Oppenheimer published a paper in which he used the new quantum theory to predict the intensities of spectral lines of the hydrogen spectrum and transition probabilities between energy levels and detailed calculations on the photoelectric effect among many other things. His work was a more complete solution than earlier work by the giants of the era Dirac, Pauli and Schrödinger.

But more lasting has been the influence of his work in molecular physics: in work done jointly with Max Born at the University of Göttingen in Germany, a famous technique was invented, the Born-Oppenheimer approximation. In this approximation the motion of nuclei could be separated from the motion of electrons so that the electron wavefunction depends on the positions of nuclei but not their motion. The approximation works because electrons are light and nuclei are heavy. Electrons and nuclei exchange forces but the electrons being much lighter have much greater accelerations (by a typical factor of 1000). The electrons immediately respond to the force, but the nuclei do not. For all practical purposes the nuclei can be thought to be at rest. The Born-Oppenheimer approximation is still used by physical chemists today.

In the note on Antiparticles we talked about Dirac's exceptional equation. Dirac's first reaction was to consider the "hole", created in the vacuum when a photon ejects an electron from one of the negative energy states, as representing a proton. It was Oppenheimer, in a masterful paper of 1930, who showed that the positively charged "hole" must have exactly the same mass as the electron so it could not be the proton. It was this work that essentially paved the way for search of the anti-electron, which was found two years later by C. Anderson and named the positron. Hans Bethe considers Oppenheimer's paper to be the one that led to the discovery of the positron even though there is no evidence that Anderson understood Dirac's or Oppenheimer's work.

In a beautiful paper published in 1939, Oppenheimer and H. Snyder used the equations of Einstein's General Relativity to study the fate of a heavy star after it had exhausted its thermonuclear fuels. They showed that a sufficiently massive star would collapse indefinitely and approach what we would today call a black hole (the term "black hole" was coined by John Wheeler more than 20 years later). Light emitted by the collapsing star would be getting progressively redder due to gravitational redshift (photons rising in the gravitational field would lose energy and so their frequency would decrease and hence their wavelength increase towards the red) and could only leave the star from a decreasing range of angles.



Light emitted from P would be able to escape to infinity only if emitted within the cone of angle θ. As the star collapses further, the angle θ decreases. Similarly, light from infinity would reach an observer at P only within the cones shown. So as the star collapses the observer would see the horizon rising and eventually closing in. Light streaming in through the closing cone would be massively blueshifted irradiating the hapless observer with deadly radiation.

The star would disappear, buried within its event horizon. This was work done at a time when talk of "black holes" was completely speculative. It is now recognized that this was Oppenheimer's greatest contribution to Physics and one that could have earned him a Nobel prize had he lived longer. Oppenheimer himself thought his work on electrons and protons (the one referred to above done in 1930) was his best work.

In the same year, 1939, in another landmark paper Oppenheimer and G. Volkoff examined the stability of neutron stars (the remnants of very massive stars after the supernova stage). They showed that just as there was an upper limit to the mass of a white dwarf, the Chandrasekhar limit, there was similarly an upper bound to the mass of a neutron star. This is now known as the Oppenheimer-Volkoff limit. When this limit is surpassed, the neutron star cannot remain stable and is doomed to collapse to a black hole.

Oppenheimer was revered by his students and postdocs. But not everyone had a favorable opinion of him. Freeman Dyson, who was hired by Oppenheimer at the Institute of Advanced Study at Princeton (Einstein was also there), thought of him as “unlikable” and “a good but undistinguished physicist” (Graham Fermelo in *Remembering Freeman Dyson* in Scientific American, April 12, 2020) who spent too much time in committees in Washington rather than doing physics in his office. And others thought of him as an intellectual snob and a “poseur”.

Either way, Oppenheimer’s work in Physics was, by any account, significant. And he definitely left his mark on the 20th century as the “father of the atomic bomb”.