Einstein's Space-Time

Einstein took the first step in the quantization of light in his miracle year, the *annus mirabilis* of 1905, while a patent clerk at the Patent Office in Bern Switzerland. The four papers published in 1905 had all addressed important problems of the time with an impact in physics that reverberates to today. Here are the titles and the physical dominoes that fell as Einstein marched through the year:

1. Light quanta hypothesis (March)
   On a Heuristic Point of View Concerning the Production and Transformation of Light

2. Brownian motion (May)
   On the Motion of Small Particles Suspended in Liquids at Rest Required by the Molecular-Kinetic Theory of Heat

3. Special relativity (June)
   On the Electrodynamics of Moving Bodies

4. $E = mc^2$ (September)
   Does the Inertia of a Body Depend upon its Energy Content?

These include the origins of both space-time and quanta: the view of deterministic causal space-time coordination of dynamics emerging from relativity and the view of wave-particle duality when particles are endowed with the quantum of action. However, Einstein viewed the light quanta paper as the truly revolutionary one, although not necessarily the path he viewed toward the future. Einstein had proposed that under certain circumstances monochromatic light with frequency ν behaves as if it consists of light quanta or particle-like objects with energy $E = h\nu$, now called *photons*. This included understanding the important photoelectric effect, the emission of electrons from a metal surface irradiated by light with frequency ν above the threshold given by the work function of the metal, which led to Einstein's Nobel Prize in physics in 1921. At that point, the Nobel committee appears to have been in a state of indecision regarding Einstein's work on space-time; Einstein was awarded the Nobel prize only for the photoelectric effect and not for the special theory of relativity.

Prior to developing his theory of gravitation, Einstein's special relativity of 1905 had incorporated the implications that the speed of light c is invariant for all inertial observers in constant motion. This led to the four-dimensional space-time picture, Figure 5.8, in which events are constrained by *light cones* pointing into the past and future along which light can travel, which confine the time-like trajectories of any particles with mass and put restrictions on communication with other particles outside the light-cone due to the finite speed of light. The four-dimensional space-time view was actually put forward by Hermann Minkowski (1864-1909), Einstein's former

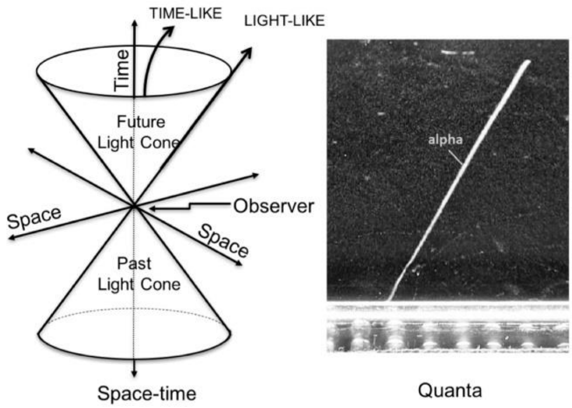

Figure 5.8: Space-time: Constraints on dynamics within space-time as required by relativity. Quanta: Linear tracks in space-time within a cloud chamber originating from spherical wave-functions of alpha particles, an early enigma for measurement.
Cloud chamber image: Julien Simon, Cloudylabs

professor, as the proper setting for Einstein's special relativity, although he did not live long enough to witness its dominance within 20th century physics. An important contribution by Minkowski is the concept of *proper time* τ comprising both space and time, which is the same for all inertial observers. And likewise, the *proper mass* m (also the *rest mass*) relates to the energy and momentum through the equations

$$(c\tau)^2 = (ct)^2 - r^2 \tag{5.1}$$

$$(mc^2)^2 = E^2 - (pc)^2 \ . \tag{5.2}$$

Minkowski had summarized this as [359]:

> *Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality.*
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That is, significant quantities in terms of an independent reality are not individually space or time or energy or momentum, but rather proper time and proper mass.