= 2?? is the angular frequency , and ? =
h / 2? is the reduced Planck constant .
Since p points in the direction of the photon 's propagation , the magnitude of the momentum is
<formula>
The photon also carries a quantity called spin angular momentum that does not depend on its frequency . The magnitude of its spin is <formula> and the component measured along its direction of motion , its helicity , must be ± ? . These two possible helicities , called right @-@ handed and left @-@ handed , correspond to the two possible circular polarization states of the photon .
To illustrate the significance of these formulae , the annihilation of a particle with its antiparticle in free space must result in the creation of at least two photons for the following reason . In the center of momentum frame , the colliding antiparticles have no net momentum , whereas a single photon always has momentum (since , as we have seen , it is determined by the photon 's frequency or wavelength , which cannot be zero) . Hence , conservation of momentum (or equivalently , translational invariance) requires that at least two photons are created , with zero net momentum . (However , it is possible if the system interacts with another particle or field for the annihilation to produce one photon , as when a positron annihilates with a bound atomic electron , it is possible for only one photon to be emitted , as the nuclear Coulomb field breaks translational symmetry .) The energy of the two photons , or , equivalently , their frequency , may be determined from conservation of four @-@ momentum . Seen another way , the photon can be considered as its own antiparticle . The reverse process , pair production , is the dominant mechanism by which high @-@ energy photons such as gamma rays lose energy while passing through matter . That process is the reverse of " annihilation to one photon " allowed in the electric field of an atomic nucleus .
The classical formulae for the energy and momentum of electromagnetic radiation can be re @-@ expressed in terms of photon events . For example , the pressure of electromagnetic radiation on an object derives from the transfer of photon momentum per unit time and unit area to that object , since pressure is force per unit area and force is the change in momentum per unit time .

= = = Experimental checks on photon mass = = =

Current commonly accepted physical theories imply or assume the photon to be strictly massless . If the photon is not a strictly massless particle , it would not move at the exact speed of light , c in vacuum . Its speed would be lower and depend on its frequency . Relativity would be unaffected by this ; the so @-@ called speed of light , c , would then not be the actual speed at which light moves , but a constant of nature which is the maximum speed that any object could theoretically attain in space @-@ time . Thus , it would still be the speed of space @-@ time ripples (gravitational waves and gravitons) , but it would not be the speed of photons .
If a photon did have non @-@ zero mass , there would be other effects as well . Coulomb 's law would be modified and the electromagnetic field would have an extra physical degree of freedom . These effects yield more sensitive experimental probes of the photon mass than the frequency dependence of the speed of light . If Coulomb 's law is not exactly valid , then that would allow the presence of an electric field to exist within a hollow conductor when it is subjected to an external electric field . This thus allows one to test Coulomb 's law to very high precision . A null result of such an experiment has set a limit of m ? 10 ? 14 eV / c2 .
Sharper upper limits on the speed of light have been obtained in experiments designed to detect effects caused by the galactic vector potential . Although the galactic vector potential is very large because the galactic magnetic field exists on very great length scales , only the magnetic field would be observable if the photon is massless . In the case that the photon has mass , the mass term <formula> would affect the galactic plasma . The fact that no such effects are seen implies an upper bound on the photon mass of m < 3 × 10 ? 27 eV / c2 . The galactic vector potential can also be probed directly by measuring the torque exerted on a magnetized ring . Such methods were used to obtain the sharper upper limit of 10 ? 18eV / c2 (the equivalent of 1 @.@ 07 × 10 ? 27 atomic mass units) given by the Particle Data Group .
These sharp limits from the non @-@ observation of the effects caused by the galactic vector

potential have been shown to be model dependent . If the photon mass is generated via the Higgs mechanism then the upper limit of m ? 10 ? 14 eV / c2 from the test of Coulomb 's law is valid .

Photons inside superconductors do develop a nonzero effective rest mass ; as a result , electromagnetic forces become short @-@ range inside superconductors .

= = Historical development = =

In most theories up to the eighteenth century , light was pictured as being made up of particles . Since particle models cannot easily account for the refraction , diffraction and birefringence of light , wave theories of light were proposed by René Descartes (1637) , Robert Hooke (1665) , and Christiaan Huygens (1678) ; however , particle models remained dominant , chiefly due to the influence of Isaac Newton . In the early nineteenth century , Thomas Young and August Fresnel clearly demonstrated the interference and diffraction of light and by 1850 wave models were generally accepted . In 1865 , James Clerk Maxwell 's prediction that light was an electromagnetic wave ? which was confirmed experimentally in 1888 by Heinrich Hertz 's detection of radio waves ? seemed to be the final blow to particle models of light .

The Maxwell wave theory , however , does not account for all properties of light . The Maxwell theory predicts that the energy of a light wave depends only on its intensity , not on its frequency ; nevertheless , several independent types of experiments show that the energy imparted by light to atoms depends only on the light 's frequency , not on its intensity . For example , some chemical reactions are provoked only by light of frequency higher than a certain threshold ; light of frequency lower than the threshold , no matter how intense , does not initiate the reaction . Similarly , electrons can be ejected from a metal plate by shining light of sufficiently high frequency on it (the photoelectric effect) ; the energy of the ejected electron is related only to the light 's frequency , not to its intensity .