SECTION 2

The Wrong Choice: The Matter Wave Problem and the Photon

THE WAVE-PARTICLE DILEMMA

The wave - particle dilemma is how to resolve that light exhibits behavior only explainable as it being an electro-magnetic (E-M) wave phenomenon yet light also exhibits behavior that would appear to be only explainable as it being of particle nature. The evidence for the wave nature of light is extensive including the wave behaviors of: reflection, interference, refraction, diffraction, frequency, wavelength, polarization, and so forth and the highly successful Maxwell's Equations describing it.

Then phenomena appeared that seem to require a particle nature of light hence its particle name, "Photon". Those phenomena were the failure at short wavelengths of the theoretical Rayleigh-Jeans law of black body radiation, then the photoelectric effect and the line spectra of gases. This evidential wave-particle duality led to the concept of the photon as a particle in the form of a "wave packet". But, the particle nature of the photon still has a number of problems.

A radially outward wave in free space tends to spread out as it propagates, but its deemed particle photon wave packets must be considered as staying together like a particle. The E-M wave front is continuous, but a front of propagating particles involves the particles' moving radially from the source with the distance between particles increasing with distance from the source and nothing in the spaces between.

E-M radiation is produced by acceleration of charge and must produce E-M propagation that is spatially symmetrical to the charge's motion, but the particle theory requires that the radiation travel away from the accelerated charge as a specific particle in some specific direction without symmetry. The next particle may be in another direction, the next in a third, and so on, so that a large number of radiated particles exhibit a dispersion pattern somewhat like that which the wave field would, but that still is behavior that is inconsistent with the wave aspect.

When waves encounter an impenetrable barrier with an aperture in it, the portion of the waves that encounter the aperture and pass through propagate from its far side as if it were a new source of radiation, that is in all available outward directions. Particles in such a circumstance, that is those particles which encounter the aperture instead of the barrier, should simply continue traveling in straight paths. If the particles (because said to be packets of waves) were to propagate in the fashion of waves from the aperture they would either have changed from particle to wave, or have each subdivided into numerous particles, or have cooperated by leaving the aperture in random directions simulating the behavior of a wave field

THE MATTER WAVE PROBLEM

In the early 20th Century (1924) DeBroglie proposed that, since light, which was then considered to be a purely wave phenomenon, had been found to appear sometimes to exhibit particle behavior; perhaps matter, which was accepted as being particle in nature might sometimes exhibit wave behavior. DeBroglie reasoned that, the wavelength of a photon being equal to Planck's constant, h, divided by the photon's momentum, the same relationship should apply to a particle of matter -- it having a wavelength of h divided by the particle momentum.

The reasoning was as follows. First considering a photon, its energy is

(2-1) $$W_{wave} = h \cdot f$$

where h is the Planck Constant and f is the frequency.

The energy equivalent of a mass, m, is

(2-2) $$W_{mass} = m \cdot c^2$$

where m is the mass and c is the speed of light.

While the photon's rest mass is zero it has kinetic mass corresponding to its energy. If the photon equivalent mass, m, actually appears as a wave its energy as a wave must be the same as its energy as a mass. Therefore

(2-3) $$\begin{aligned} W_{mass} &= W_{wave} \\ m \cdot c^2 &= h \cdot f \\ m &= \frac{h \cdot f}{c^2} \\ &= \frac{h}{\lambda \cdot c} \end{aligned}$$

and, finally,

(2-4) $$\begin{aligned} \lambda &= \frac{h}{m \cdot c} \qquad \text{[solving (2-3) for } \lambda\text{]} \\ &= \frac{h}{\text{photon momentum}} \end{aligned}$$

by recognizing that momentum is defined as the product of mass and its velocity and the velocity of the photon is c.

DeBroglie hypothesized that the wave aspect of a particle of matter should have an analogous wavelength, λ_{mw}, that should be

(2-5) $$\lambda_{mw} = \frac{h}{\text{particle momentum}} = \frac{h}{m \cdot v}$$

This suggestion of DeBroglie was soon verified by Davison and Germer who obtained electron diffraction patterns and found that the observed wavelengths of the electron matter waves corresponded well with DeBroglie's formulation.

At that point one would think that the duality of matter, as of light, was established and that extensive further investigation of matter waves would have resulted. But that was not the case and the reason was a fundamental problem that could not be overcome – the matter wave frequency.

If one reasons, analogously to the derivation of λ_{mw}, that the kinetic energy of the particle of matter should correspond to its matter wave frequency, f_{mw}, as

$$(2\text{-}6)\qquad f_{mw} = \frac{W_k}{h} = \frac{\frac{1}{2}\cdot m\cdot v^2}{h}$$

then the velocity of the matter wave is

$$(2\text{-}7)\qquad v_{mw} = \lambda_{mw}\cdot f_{mw} = \left[\frac{h}{m\cdot v}\right]\cdot\left[\frac{\frac{1}{2}\cdot m\cdot v^2}{h}\right] = \tfrac{1}{2}\cdot v$$

a result that states that the matter wave moves at one half the speed of the particle. That is obviously absurd as they must move together each being merely an alternative aspect of the same real entity. For them not to move together would be as absurd as for the particle aspect of light to move at a different speed than its wave aspect, the photon not arriving coincident with the *E-M* wave.

It is no help in resolving this difficulty if relativistic mass is used (as it should be in any case) since the same mass appears in both numerator and denominator of equation *(2-7)* where they simply cancel out.

It is also no help to hypothesize that it is the total energy, not just the kinetic energy, that yields the matter wave. Such an attempt attributes a matter wave to a particle at rest. It also gives the resulting matter wave velocity as c^2/v which has the matter wave racing ahead of its particle. No, the two must keep pace with each other since they are the same thing merely looked at in one or the other of two alternative ways.

<u>It was the inability to resolve this problem</u> that led to the loss of interest in matter waves and essentially the end of further inquiry with regard to the wave aspect of matter. That resulted in modern physics in the complete dominance of the particle form of light and matter, a development initiated by the work of Planck and Einstein.

PLANCK'S AND EINSTEIN'S QUANTA

The amount of energy radiated at various wavelengths from a material body varies with the temperature of the body (e.g. a piece of metal as heated hotter and hotter changes in the apparent color of its glow from dull red through orange to bright white). Experimental observations of this consistently show a characteristic pattern as in Figure 2-1, below: low energy magnitude at small wavelength, followed by a peak around a wavelength that depends on the temperature of the radiating body, further followed by a tapering off as wavelength further increases. If a theoretical curve is calculated based on E-M wave theory, the Rayleigh-Jeans law of black body radiation, and compared to the measured actual results a discrepancy appears. The theoretical curve increases without limit as wavelength becomes smaller instead of peaking and then declining toward zero.

This conflict of theoretical and actual behavior was resolved by Planck. He found that if the theoretical curve was derived upon the supposition that the radiated energy was given off in minute bursts of waves, bursts later called “quanta”, rather than as continuous waves, and that each minute burst has the energy of the product of the radiation frequency and a constant, then the theoretical curve matched the actual curve for the given temperature. That relationship is equation *(2-8)*, where f is the frequency of the radiation and h is the (then new) universal constant, subsequently named *Planck's Constant* the value of which has been found to be about $6.626\ 070\ 040(81) \times 10^{-34}$ J s.

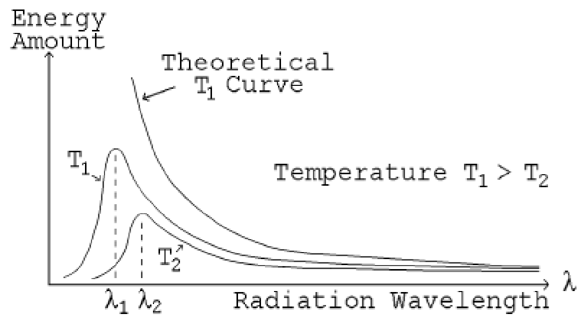

Figure 2-1

(2-8) $W = h \cdot f$

Einstein and the Photo-Electric Effect

Under suitable circumstances, it is found that when light or other E-M radiation of sufficiently high frequency shines on or encounters a material substance then electrons are given off by the substance. This *photoelectric effect* is the operating principle of television cameras, xerographic copiers, etc. The normal expectation would be that one would have to wait a shorter or longer time, depending on the intensity of the light, while it delivers enough energy to free the electrons, a heating up period so to speak. On that basis any E-M radiation should produce some electrons from the substance that it encounters if given enough time.

But, that mode of behavior is not the case. Experimental observations show that there is no heating up time, no apparent energy accumulation. Electrons are liberated by the incident light immediately if they are to be liberated at all. There is a threshold frequency, however, below which the light never releases electrons, at and above which electrons are always released, and then at which the rate at which electrons are given off depends on the light intensity.

The threshold frequency is different for different substances on which the light is shined. Furthermore, the electrons are given off with various individual energies, but the maximum energy of the released electrons depends directly on the light frequency. Figure 2-2, below, depicts this photoelectric effect behavior for different substances. The slope of all such lines turns out to be the same, as depicted in Figure 2-2 below. Furthermore, the slope turns out to have the same value as Planck's constant, h, the constant that Planck found necessary to explain black body radiation.

Einstein explained this behavior by postulating, similarly to Planck's assumption for black body radiation, that the light travels in packets of energy each containing the energy of equation *(2-8)*, $W = h \cdot f$. These packets of light energy were given the name *photons* and they were assumed, like matter particles, to be a discrete package traveling in one specific direction.

Einstein's hypothesis was that if a photon that is part of the incident light and that encounters an electron in the substance has enough energy W due to its frequency f so that the photon energy is greater than the energy binding the electron into the substance, then the electron will be released. Photons at frequencies below that threshold would not have enough energy to free an encountered electron. A photon of energy greater than the threshold would not only release the electron but would impart its excess energy to the electron as kinetic energy of motion. The rate at which electrons are released would depend on the rate of photons with time, which corresponds to the intensity of the light.

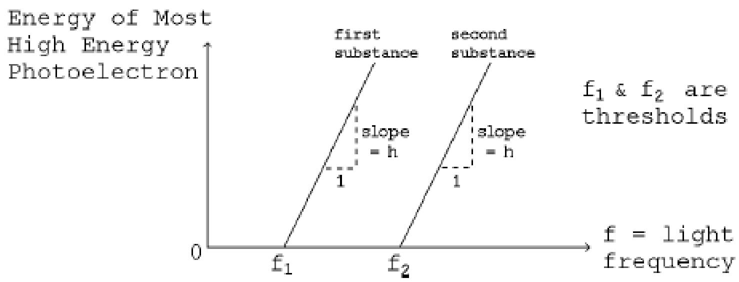

Figure 2-2

The Effect on the Foundations of Quantum Mechanics

The beginnings of Quantum Mechanics was distorted by the mistaken understanding of Planck's solution to the problem of a misfit of the classical Rayleigh-Jeans Law describing black body radiation. The mistaken understanding was the assumption that the quantization which successfully corrected the Rayleigh-Jeans curve represented the energy of actual particles. That was an over-assumption from the data. The data only showed that the energy transfer in black body radiation, a transfer from the hot radiating body mass to the propagating radiation, occurred in discrete amounts, quantized packets of energy change / transfer in amount $W = h \cdot f$. It makes no statement about the form of that radiation being like a particle.

Likewise, Einstein in explaining the photoelectric effect deemed that the incident light had to be in the form of particles. For Einstein: yes, discrete amounts of energy, $W = h \cdot f$, as with Planck, but also those in "packets" of some kind traveling like discrete matter particles in one specific direction. However it is impossible for natural light to be a discrete mono-directional particle; it must be a wave with a smoothly continuous lateral wave front, as follows.

Analysis of the Photon from Its Generating Source

To resolve the problem of the nature of the photon it is necessary to go first to the constraints on what a photon is as they are imposed by its source, the transition of an atomic orbital electron from an outer to an inner orbit which transition must fit and match to, the following requirements.

- The transition is a change from the initial state to the final state as in part of a single cycle of an oscillation. It is not a changing to a different state and then returning back to the original state as in a full cycle of an oscillation.

- To avoid an infinite rate of change, which is impossible, the transition must be a smooth variation, without any sudden "jump".

- The resulting radiation exhibits all of the characteristics of Maxwellian electro-magnetic wave and is at one simple frequency, the photon frequency. It therefore must be in the form of a simple sinusoid.

- The theory of information in communications shows that at least a sample every half-cycle of an oscillation is required to specify it sufficiently. Therefore, at least a half cycle of the photon oscillation is required to specify it.

Therefore, the photon must be in the form of a half-cycle of a sinusoidal function of time. Beyond that, the following.

- In general, magnetic field is directly proportional to the velocity of the moving electric charge producing that field. Therefore the magnetic field of the photon is directly proportional to the transitioning electron's velocity. Since the photon magnetic field must be a half-cycle sinusoid the transitioning electron's velocity variation must be of a half-cycle sinusoid form.

- The electron velocity must vary in accordance with the above from the stable velocity of the initial orbit through a period of increase and ending in the stable velocity of the final orbit. (The potential energy lost in the move to a lower orbit appears half in the emitted E-M radiation, the photon, and half in the increase in electron kinetic energy due to its greater velocity in the inner orbit).

The combination of these factors results in the specification that the photon must be a half cycle of a pure sinusoidal type variation behaving as in the following figure 2-3.

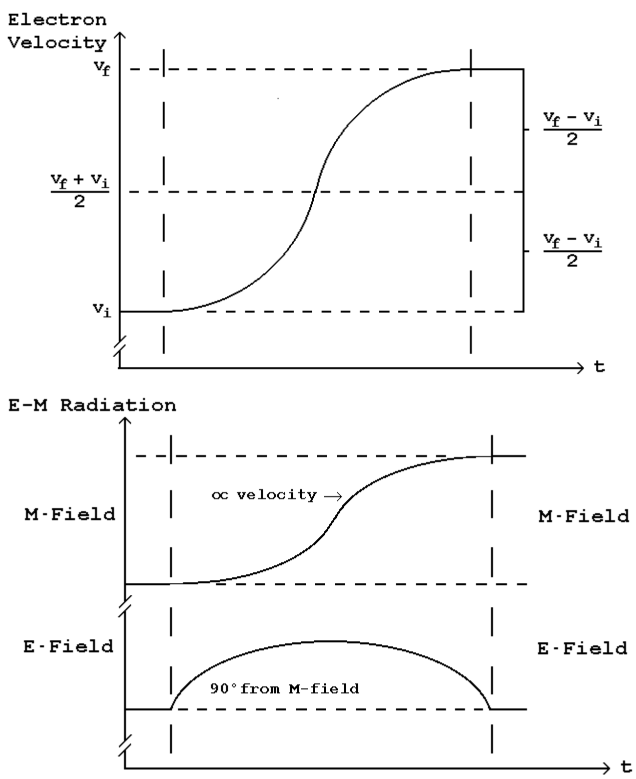

Figure 2-3 – The Orbit Transitioning Photon Generating Electron Behavior

The electron, traveling from its initial outer orbit to its final inner orbit with its velocity gradually increasing in a sinusoidal manner as in Figure 2-3, follows a path as illustrated in Figure 2-4 below, and emits an E-M wave field in “doughnut form” as in Figure 2-5, below, relative to its instant-by-instant varying vector velocity direction at each instant of the transition.

The peculiar shape of that field because of the directional orientation of the “doughnut” swinging through a substantial portion of a full circle according to the path of the electron’s orbital descent causes the propagated E-M wave to contain the requisite form, angular momentum and energy for causing an encountered orbital electron elsewhere to be elevated to a higher orbit equivalent to the higher orbit that the electron previously descended from.

The propagated E-M wave burst contains and transmits both that energy and that angular momentum.

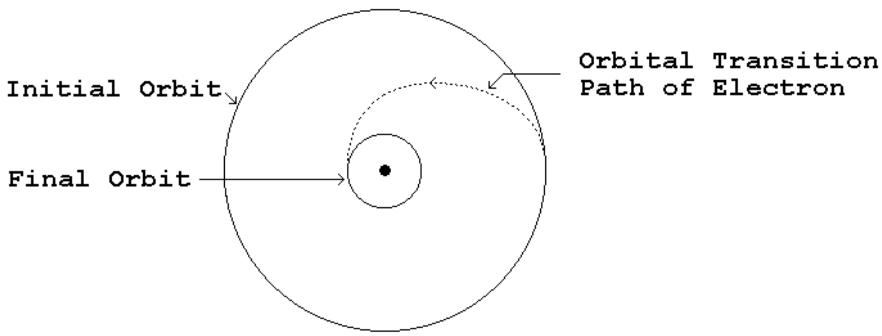

Figure 2-4 – Typical Electron Outer-to-Inner Orbit Change Path [Schematic]

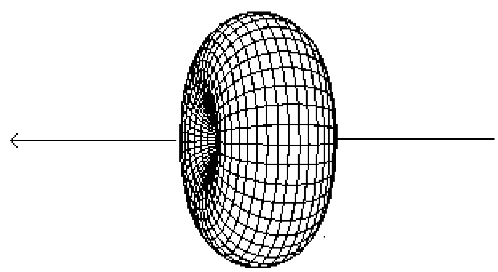

Figure 2-5 – Instantaneous Electro-Magnetic Radiation Pattern [doughnut shape] of a Single Electron Traveling as Shown.

Knowing the time duration of the electron's orbital transition relative to the electron orbital period is helpful in visualizing the process. The orbital transition takes place in the time of one-half cycle of the photon's frequency. Letting “D[xx]” symbolize “the duration of xx” then

$$\text{(2-9)}\quad D\,[\text{orbital transition}] = D\,[\text{photon}] = \frac{1}{2\cdot\text{photon frequency}}$$

Let n be the orbit number, an integer representing the number of matter wavelengths in the orbit. The electron orbital velocity is proportional to $1/n$. Its matter wave frequency is proportional to $1/n^2$. The photon frequency is equal to one-half the difference between the initial and final orbits matter wave frequencies. From those, the duration of the orbital transition in terms of the duration per orbit in the final orbit is

$$\text{(2-10)}\qquad \frac{D\,[\text{orbital transition}]}{D\,[\text{final orbit}]} = \frac{n_{initial}^2}{n_{final}\left[n_{initial}^2 - n_{final}^2\right]}$$

For some selected orbit transitions the results are as in Table 2-1, below.

n_i	n_f	Transition/ final orbit	n_i	n_f	Transition/ final orbit
2	1	4/3	4	3	16/21
3	1	9/8	5	3	25/48
3	2	9/10	6	3	36/81
4	2	4/6	7	3	49/120
5	2	25/42			

Table 2-1 – Typical Electron Outer-to-Inner Orbit Transitions

The transition takes place in $1\text{-}^1/_3$ final orbit periods at most [$n_i = 2,\ n_f = 1$], and in less than 1 final orbit period for most cases [$n_f > 1$]. The orbit transition and photon emission take place with the electron traveling a significant portion of an orbit around the atomic nucleus in all cases.

Looked at another way, the transitioning electron travels in the range of on the order of $180°$ to $360°$ of a circular orbit. Its path being curved its direction at instants during the transition changes by on the order of $180°$ to $360°$. <u>Such a path is completely incompatible with a particulate photon being emitted in some one specific direction by that transition</u>.

Since 1960, when the first laser was made and operated, there have been two different forms of light. "*<u>Natural Light</u>*" The primary source of light is the transition of an orbital electron of an atom from a "higher" "stable" orbit inward to a less high stable orbit as just above addressed. It is impossible for such light to be unitary mono-directional particles. It is a form of wave that is generally of broad wave fronts and tends to spread out in space. Photons of such light are half-cycle sinusoidal waves in bursts of total energy of $W = h \cdot f$.

"*<u>Coherent Light</u>*" An important but much less ubiquitous form of light is that generated by a laser. A laser is a device that emits light through optical amplification based on the stimulated emission of electromagnetic radiation. The stimulated emission initially produces the above primary source kind of light but the amplification process results in the light becoming coherent. Coherent light is a beam of photons, particle like light waves, again half-cycle sinusoidal waves in bursts of energy $W = h \cdot f$, that have the same frequency and waveform and are in phase. Only a beam of coherent laser light is able to largely resist spreading and diffusing.

It is clear from all of the above that for "natural light" it is impossible that it travel outward away in a single specific direction as required for the photon-particle hypothesis. That role is restricted to "coherent light". Furthermore, there are other problems with the "natural light" particle hypothesis.

Perhaps the greatest other problem with the "natural light" photon-particle theory is as follows . The wavelength of light is in the range of 10^{-7} meters . Atomic dimensions are on the order of 10^{-10} meters so that if a photon is to contain wavelength data relevant to the light that it represents, it must then have dimensions that are on the order of 10^3 = 1000 times the size of an entire atom let alone than the size of a much smaller orbital electron. Clearly this is completely at variance with the photon-particle explanation of the photo effect and line spectra of atoms.

For example, in the instance of absorption of a photon-particle causing the raising of an orbital electron to a higher orbit or to free of its site there would be, relatively speaking, a *football size photon* interacting with a *sand grain size atom*, the football-photon managing to focus its action solely on one *germ size electron* in the *sand grain size atom* without disturbing any of the rest of the atom.

The photoelectric effect has the same problem. For a photon-particle to eject an electron from an encountered metal material means a *football size photon* interacting with a *germ size electron* in the material composed of *sand grain size atoms* without disturbing anything other than the particular *germ size electron*.

THE CORRECT PHOTOELECTRIC EFFECT

Einstein received the Nobel Prize for his explanation of the photoelectric effect. That explanation depended on his concept of light as consisting of unitary mono-directional particles concentrated in a laterally narrow body able to pass completely and freely through narrow slits and focus all of its action on objects as minute as a particular electron among others in a particular atom, those particles subsequently given the name “photons”.

But now, having found that, except for narrowly collimated light in wave bursts from a laser, it is impossible for light to be of particle form and must be a form of wave with a wave front much more broad that that of Einstein’s photon the issue arises “what is the correct mechanism of the photoelectric effect ?

How does incoming E-M radiation become absorbed by an atom’s electron and excite it to being entirely free of the atom as in the photoelectric effect ?

First it is necessary to consider what it is that is absorbed. The light or E-M radiation available for absorption by and excitation of an electron is the same E-M radiation given off by an electron falling from a higher to a lower energy orbit. The radiation from any single outer-to-inner-orbit transition contains the energy, angular momentum and force that are exactly correct to cause an electron to execute the inverse transition.

However, the E-M wave from a single electron orbital transition must radiate outward from the transitioning electron. It is impossible for all of that radiation to encounter one other single electron. Rather, any single electron encounters a very small portion of that radiation’s total wave front.

E-M radiation consists of a large number, a continuum, of waves propagating in the form of individual half-cycle sinusoids of radiation. A light beam or other radiation is a plethora of such radiation bursts, burst upon burst, side by side, in front, behind, overlapping, running together, and on and on. It is from among that immense number of very small parts of myriad electron inward transition radiations that that which an electron needs to perform an outward transition is found.

The wave front of a single such radiation burst, the output of a single electron's inward transition, disperses in space as it travels outward from its source. Only a quite small part of the total wave front of such an individual burst can encounter and interact with another particular electron. But, the radiation encountering a single particular electron is the sum of a very large number of such individual small parts of the radiation from individual electron inward transitions.

Out of the plethora of arriving half-cycle sinusoids, more precisely the plethora of small portions of their individual total wave fronts, the electron responds to an instantaneous sum of arriving waves that may or may not have the energy and momentum sufficient to free the electron from its atom - the photoelectric effect.

In a beam of light shined on a material, such as the light shined on a substance to yield the photoelectric effect, there is a very large number of radiative type interaction half-cycle sinusoid bursts propagating as waves. These constitute the beam of light. Some portion of them will coincide properly in frequency and timing and have sufficient collective amplitude at some electron to produce the observed photoelectric behavior.

"Sufficient collective amplitude" is the state in which the sum of the myriad minute parts of numerous transitions of the correct type adds up to being equal to or greater than the effect as if all of the radiation had passed intact from one such inward transitioning electron directly to the encountered electron (as the photon theory deemed it).

But, why is the energy magnitude dependent only on the frequency; how does wave amplitude enter into the process ? The waves inverse square disperse as *Propagated Outward Flow* does, so that the amplitude of each individual burst decreases steadily in inverse square manner from its value at the moment of the interaction that created it. The farther that an absorptive interaction is from the source of incoming radiation the greater the number of individual bursts, each contributing a small portion of the requisite amplitude, that are required to become the "sufficient collective amplitude" for an absorptive interaction to be able to take place.

The amount of energy naturally depends on frequency. The higher the frequency the more rapidly the E-M radiation oscillates. The E-M radiation carries the ability to cause corresponding change in motion in encountered charged particles. It requires more energy per time to make a rapid change than to make a gradual one. A shorter period (higher frequency) half-cycle sinusoid must contain directly proportional greater energy to produce the proportionally more rapid change.

CONCLUSION

The concept in general of the particle nature of light has been dominant in physics for over a century. That concept developed long before the invention of the laser, a device able to generate particle-like photons as treated in Section 9. Likewise, neglect of the wave nature of matter and focus on its particle conception has long dominated physics.

Having now found that it is impossible for normal light to be unitary mono-directional particles and, therefore it must be a form of wave, we now proceed to resolving the matter wave frequency problem and thus opening the wave nature of matter for analysis.