What is an electron?

A new model: the phase-locked cavity

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What is an electron beyond being just a unit of charge? Why do we have to push an electron, or a car, with a specific force to make it move? Why does it carry on moving after we stop pushing? Why, in the limit, is the push quantised? Three-quarters of the way through the twentieth century there was no satisfactory answer to these questions but recent research in the Electronics Laboratories of the University of Kent at Canterbury may have provided the answers.

THE electrical or electronic engineer can often get by without considering all the properties of the electron and frequently regards it simply as a unit of electrical charge. Occasionally he may encounter a problem in electron optics or physical electronics where he has to recognise that the electron has a mass, a magnetic moment and quantised angular momentum and he will accept that it obeys the quantum laws and Fermi-Dirac statistics. Electrons have become so useful that their properties in all sorts of circumstances are very well known and rules for their behaviour are fully documented. By the very nature of these rules many of them are *ad hoc;* they were propounded to explain the idiosyncrasies of the electron, and sometimes matter in general, in order to provide working rules to account for its behaviour in all manner of circumstances. Thus the quantum theory has gradually incorporated further rules to account for more sophisticated observations and these rules have become an accepted part of physics. They work, and for many people that is sufficient, so why bother to question why nature obeys these rules if the rules enable us to achieve all the technological wonders of the age?

The same applies to Newton's laws; they are usually accepted as basic laws of physics yet they are only rules, laid down by Newton to account for the observation of the behaviour of matter. There has to be a reason for Newton's laws, just as there has to be a reason for the quantum theory, the charge on the electron and all its other properties. Really what we have is a wonderful computer programme that has evolved over the ages and to which we may refer for the solution of nearly all of our problems. The curious thing is that we don't, or at least didn't, know *why* the programme works.

Why have a few people worried about why it works? Let me give you an analogy. In these days of integrated circuits it is very easy to build quite complicated electronic systems by plugging integrated circuits together in a rational manner and relying on the fact that the manufacturers have done a good job in specifying the overall parameters and transfer function of each unit. It is not necessary to know precisely what goes on inside each integrated circuit provided that we stick to the rules. Or is it? There are vast possibilities open to the current range of integrated circuits, microprocessors and the like, but who would suggest that we stop all further research into physical electronics and simply accept the present state of the art for all future applications? It is only by digging down into the fundamentals that we are likely to achieve a really major break-through in the future.

Until very recently, in order to explain the electron, its inertia, its detailed quantised behaviour, its charge and its other properties as a particulate entity, at least half a dozen separate postulates were required. Some of these postulates are embodied in the separate rules comprising the quantum theory, and quantum mechanics has six postulates (Van der Waerden, 1973). Other postulates like those concerning inertia and charge are even more mysterious for these properties have assumed such a traditional place in our teaching that their existence is automatically accepted without question. Einstein always seemed content to accept Ernst Mach's postulate for the origin of inertia (that its origin was in the influence of the distance masses in the Universe) but he had considerable reservations about the quantum postulates. Werner Heisenberg (1973) commented: "I had a discussion with Einstein about this problem in 1954, a few months before his death. It was a very nice afternoon that I spent with Einstein but still when it came to the interpretation of quantum mechanics I could not convince him and he could not convince me. He always said: 'Well, I agree that any experiment the results of which can be calculated by means of quantum mechanics will come out as you say, but still such a scheme cannot be a final description of Nature'." It is clear that Einstein had a fundamental conviction in the basic beautiful simplicity of Nature. To Einstein the quantum theory was simply a succession of *ad hoc* solutions with the greater truth hidden somewhere underneath. It is surprising how this echoes the earlier difference of conception on the nature of photons where Planck and Bohr held on to simple classical concepts and Einstein, on that occasion, was the radical, postulating a complication in an otherwise simple conception of light.

Heisenberg's views on electrons, photons and other particles were very complicated and caused considerable dissension in his audience. Dirac, who was present when Heisenberg read a paper, was not entirely happy: "I wonder whether the electron should not be considered as an elementary particle. It may be that I am prejudiced because I have had some success with the electron and no success with other particles. I would like to hear Heisenberg's view on that." Heisenberg's reply well illustrates the attitude of a whole school of thinkers who are devoted to the extreme quantum picture of corpuscular particles, to the possible exclusion of a simple underlying theme which, in the same breath, they state may well exist: "I cannot see that one could consider the electron as an elementary particle in the old sense, because an electron can produce light quanta. Light quanta can produce baryons. So actually the electron is connected with this world of baryons and hadrons and so on. So I don't see that you can separate it out. As soon as an electron has these interactions, then, of course, it is surrounded by a cloud consisting of all these other things". The rigidity of Heisenberg's thinking is illustrated beautifully by his use of the phrase "of course" in the last sentence. It is probably worth noting that Heisenberg lost on points in the discussion which followed.

It is generally acknowledged that the quantum theory cannot solve the mystery of the electron for it starts too far up the scale and uses as its postulates the properties which are already embodied in the electron. The quantum description of an electron therefore properly agrees with these properties but it tells us nothing of the substance from which it is made or how it is held together. A good account may be found in Rohrlich (1973) and see also Feynman (1964).

Most of the attempts to model the electron have relied basically on classical concepts, a distribution of electric charge held together by unknown forces named Poincaré stresses after their propounder. Problems arise with this model for if the bits of charge move in the field of the particle as a whole they are acted upon by a Lorentz force and it has not been possible to establish a model which satisfies the observed features of the particle. In particular the 'electromagnetic mass' of these models differs slightly from the rest mass derived from relativity theory.

The discovery that electrons have an intrinsic spin presented further difficulties with this model, for the angular momentum turned out to be almost exactly half that which would be given by classical physics. Furthermore, the ratio of magnetic moment to angular momentum for an electron about its own axis turned out to be twice that which applied when the electron was in orbit about a nucleus.

This 'plum pudding' model of the electron assumes that electric charge is fundamental, for it in no way accounts for it, and it further requires that the charge can be spread throughout the electron. This implies that the unit of charge can be broken up into many separate bits of unknown substance. The electric field, in line with traditional electromagnetism, is assumed to arise from the charge and is therefore thought of as a secondary phenomenon. This leads to a further difficulty with this model, for measurements show that the electron appears as a point charge, and yet this implies an infinite energy for the field at at the centre. Attempts to avoid this difficulty never seem to agree with the observed facts; for example, the 'classical radius' of the electron may be calculated for the model and turns out to be 2.8×10^{-13}cm. When measurements are made on the electron it does not seem to have any particular radius, certainly not 2.8×10^{-13}cm, and the effective radius given by the quantum theory is 137 times larger.

A very few authors have endeavoured to avoid the problems of the plum-pudding electron by postulating whirls of electromagnetic waves which might arise from non-linear solutions of Maxwell's equations. On the whole these theories have been looked upon as curiosities for they by no means accounted for the properties of an electron, but they did remove one variable by attributing the charge to a condensation of the electric field.

Radiation and electrons

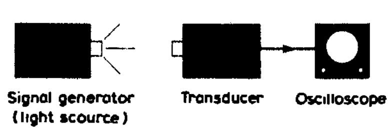
What is the connection between radiation and electrons? Clearly we can only detect radio waves by utilising their interaction with electrons or protons and we have to be very careful not to confuse the properties of the radiation with those of the electron and vice-versa. Nevertheless there are two remarkable phenomena which show that at certain precise frequencies the connections between electromagnetic waves (or photons) and electrons is absolute – they completely transform into each other. Before we consider these phenomena let us look at the way it is possible to conceive of radio waves as photons.

According to the photon concept radio waves consist of a very large

Radio waves or photons? — historical background

In his famous treatise on optics Newton stated that light consisted of corpuscles and his authority was such that his opinion dominated scientific reason until, nearly a hundred years later (1801), Thomas Young showed that the interference of light was a wave phenomenon.

In the mid nineteenth century James Clerk Maxwell showed theoretically that there should be electromagnetic waves, that light fitted this description and that there ought to be a spectrum of such waves from the lowest electrical frequencies to far above the frequency of visible light. Some years later Hertz demonstrated the existence of radio waves and the wireless transmission of telegraphic messages became a reality. Then the bombshell came: the discovery of the photo-electric effect. No one could explain how electromagnetic waves could eject electrons from metal surfaces, for the onset of emission depended upon the *frequency* of the waves. Below a certain critical frequency no electrons were ejected, irrespective of the amplitude or intensity of the waves. In 1904 Einstein accounted for this by proposing that energy and frequency were related by the now famous formula $E=h\nu$. The interpretation that he put on this formula was that light consisted of discrete bundles of energy (later called photons). The energy given by this formula had to exceed the energy binding the electron in the surface before it could be ejected. The reason why Einstein and many of his contemporaries assumed that the interpretation of $E=h\nu$ was that the light only was quantised was because they considered the electron simply as a point or a ball of charge, and, as such, it appeared that it could have none of the properties of a simple system. A macroscopic analogy could take the form of a large scale opto-electrical transducer in the form of a black box, an optical signal generator in the form of another black box and an oscilloscope to observe the output of the transducer (see figure). If then we observed that the oscilloscope registered pulses when the optical generator was applied to the transducer, it would be reasonable to assume that the generator was emitting pulsed light. This was Einstein's interpretation. But are there other possibilities? It is an elementary exercise in electronics to make a transducer with delayed feedback which will give a pulsed response from a continuous wave input, so that in the analogue case this is clearly another solution. One further possibility remains, that *both* the light and the transducer response are pulse-like, so that, going back to the interpretation of $E=h\nu$ there are three possibilities; (i) all light is quantised (photons). (ii) all light is electromagnetic waves and the response of the electron is quantised, (iii) both the light and the electron are quantised.



An unspecified light source and an unspecified opto-electrical transducer coupled to an oscilloscope. If the oscilloscope exhibits a pulsed waveform, does this imply that the light is pulsed, that the transducer has a pulse-like transfer function, or both?

It is interesting that Max Planck, the founder of the quantum theory, and Niels Bohr, the founder of modern atomic physics, would not accept the concept of Einstein's photons, especially if this implied that light was corpuscular, and they hoped for some other explanation of the effect. Planck himself had revolutionised physical concepts by postulating the quantum of action, *h*, to explain the laws of black body radiation, but he held on to the belief that the radiation itself was simple waves of the Maxwell-Hertz type. Bohr's attitude is recorded by Leon Rosenfeld (1973): "As to the photon or light quantum concept, introduced by Einstein, Bohr regarded it as a useful but auxiliary concept, one which he later called symbolical, meaning thereby that it was not an aspect of the radiation phenomenon which could be directly observed as such."

Despite his remarkable contribution to quantum theory Einstein was never happy with the quantum concept and in particular with the surrender of deterministic physics which seemed to defy the very basis of the classical principles upon which he built up the principles of relativity. Twenty years later Compton investigated the behaviour of free electrons when radiated with electromagnetic waves of very high frequency and explained their behaviour by a billiard-ball like collision process between a photon and an electron, and the concept of photons as simple short wave-trains here seemed less applicable than the corpuscular bullet-like concept. Shortly afterwards Dirac welded together the quantum theory and relativity in such a way that the behaviour of electrons in general could be properly accounted for and his theory also predicted a positively charged twin to the electron, the positron, which was discovered a few years later in cloud chamber tracks of cosmic rays.

number of low energy photons which statistically behave as though they are Hertzian waves. Although no one knows what a photon looks like, it is assumed by one school that a single photon is some form of particle or corpuscle and by another school that it is a short burst of waves which nevertheless behaves as though it is purely monochromatic. The first point of view is clearly exhibited in the listing of the photon in tables of fundamental particles, despite the fact that its properties under relativistic transformations are quite different.

Photon energies at radio frequencies are extremely small, so the energy of a powerful radio signal comes from having a vast number of photons and, because there are a vast number, the statistical combination of all the photons synthesises the electromagnetic waves propounded by Maxwell. Radio astronomers can receive spectral line signals at v.h.f. which originate in the very low energy transitions between, say, the 250th and 251st Bohr orbits of the hydrogen atom (conditions in interstellar space are so tenuous and collisions are so rare that these remarkable transitions can actually take place). Is one receiving corpuscular photons or simple Hertzian waves? The quantum theory tells us nothing for it avoids the issue by simply identifying the frequency ν with the energy $E=h\nu$ between the respective orbits. The emission of a photon is postulated but the mechanics of its formation and the structure of the photon remain a mystery.

If two oppositely charged spheres on the ends of a rod are spun about the centre point, then it is fairly easy to comprehend how this gives rise to very low frequency radio waves in terms of oscillating electric and magnetic fields moving outwards at the velocity of light. It is also easy to picture the situation as the rotational speed is reduced to zero for we are just left with a static dipolar electric field. If we endeavour to interpret this situation in terms of corpuscular photons it is far less easy to comprehend and becomes anomalous when we reduce the rotational speed to zero. One has either to accept the static electric field as a separate system in its own right, endowed with the ordinary field properties of Maxwell's equations or one has to preserve an entirely photon concept by postulating the existence of virtual photons to explain the properties of the system at zero frequency.

It is probably apparent that the corpuscular photon concept is not very helpful at radio frequencies although the concept of a multitude of short wave trains is not unreasonable. For example, the analysis of an open-ended resonant cavity, even when the radiation is infinitesimally weak, does not pose a problem to the radio engineer using the concept of electromagnetic waves, but try arguing it out when it is inhabited by one bullet-like photon! Similarly, feedback problems using corpuscular photon concepts are a conceptual nightmare.

It may appear from the foregoing that photons are bit of a red herring and that, apart from the photo-electric effect and various atomic phenomena, classical electromagnetic waves consisting of simple fluctuating fields are far more satisfactory. Really the problem is more fundamental and concerns the interplay of radiation and matter. Which is the more fundamental – the photon or the electromagnetic field wave? the charge or the associated electric field? It is currently fashionable to consider that all electromagnetic waves are an assembly of photons and therefore to infer that it is impossible for a photon itself to be composed of electromagnetic waves. If one considers photons to be little balls of some form of light then, clearly, the statement is logical. If, on the other hand, the photons are simply limited trains of electromagnetic waves which can add together according to Fourier principles, then the statement is quite untrue – the photons *are* composed of electromagnetic waves and the electromagnetic fields and not the photons are the more fundamental. But then, if electromagnetic fields come initially from moving charges, it would appear that the charges are really the most fundamental and the fields secondary or tertiary according to one's choice of the two viewpoints. As we shall see later, we can question this argument on similar logical grounds. If we can form the unit of charge (the electron) from electromagnetic fields then we may reduce the number of variables and simplify our conception of the universe by requiring only the existence of time varying electric fields.

About thirty years ago I constructed the first intensity interferometer. With this I had been able to measure for the first time the shapes of the radio stars Cassiopeia A and Cygnus A. (In those days there were only three radio stars, Cassiopeia, Cygnus and Taurus!) The original concept of the intensity interferometer was due to R. Hanbury Brown but he gave me a very free hand in its realisation as he was much occupied with work on the original Jodrell Bank 218ft telescope. It was quite unlike a conventional interferometer for it did not make use of the direct correlation of coherent signals but of the *fluctuations* of those signals. The correlation was performed after detection so that it might at first appear that all correlation was lost. However, random fluctuations from the various parts of the distant source beat together at the output of two detectors spaced apart by many miles on the earth's surface. The modulation is therefore cross-correlated and provides information about the source.

The intensity interferometer produced some excellent results although it had the drawback of being rather insensitive and incapable of determining the phase of the source distribution. It immediately raised the question "if it works for radio waves will it work for light waves or photons?" I had thought up a new and entirely different interferometer technique which proved much better for further work in radio astronomy for it solved many of the problems of working on very long baselines (it is now known as "phase closure" and is used over baselines of thousands of miles) so I reluctantly declined an invitation from Hanbury Brown to work on an optical version of the intensity interferometer. Hanbury Brown tried it for himself and with theoretical help from Richard Q. Twiss finally established that there was a correlation in the light from a laboratory source, and later, from starlight.

The success of these experiments caused quite a lot of re-thinking in theoretical physics at the time for, in the words of Hanbury Brown, "It appeared to show that one little photon knew what another little photon was doing!" Certainly if one looks at the situation from the point of view of fluctuating electromagnetic fields, as in the radio case, there is no problem. The important lesson which we learned at the time was this: though we may consider that in the emission and detection processes light, or a radio signal, behaves as photons, in the propagation process between source and observer it behaves as electromagnetic waves.

Are there any experiments where the wave concept fails completely? Apart from the photo-electric effect the shining example was the Compton Effect. In 1924 Compton showed that when very high frequency electromagnetic radiation (γ rays) fell on an electron, the electron immediately shot off as though it were hit by a bullet and simultaneously emitted a burst of radiation of somewhat lower frequency than that of the incident radiation. Usually the electron shot off at an angle from the direction of the original radiation and the re-emitted radiation shot off at another angle. All attempts to explain this classically failed; it really looked as though light must consist of bullet-like photons and Compton was able to account for the phenomenon entirely in terms of a billiard ball type collision of a photon incident with energy $h\nu$ and reflected with energy $h\nu'$ from a billiard ball type electron of rest mass m_0 which shot off with the kinetic energy given by the difference between $h\nu$ and $h\nu'$. Surely this was proof that photons must be particles and not just short wave trains? Last year I was able to show that it can be explained quite simply as an electromagnetic wave phenomenon provided that we identify the electron with a simple phase-locked cavity of radiation.

Earlier on we referred to two remarkable phenomena by which electromagnetic waves and electrons completely transform into each other. These are known as annihilation and pair production. Annihilation occurs when a negative electron bumps into its opposite number, a positive electron (or positron). Both particles completely disappear and from the point in space where they collided two photons of identical frequency but opposite polarisation move off at the speed of light. The frequency of these photons is such that it corresponds to the exact conservation of energy in the transformation. The rest energy of the electron is $E = m_0c^2$ where m_0 is the rest mass of the electron and c is the velocity of light. The rest energy of the positron is similarly m_0c^2. If the two particles idly bump into each other we therefore get two photons each with a frequency given quite simply by equating the energy $E = h\nu$ with the energy $E = m_0c^2$ and therefore the frequency $\nu = m_0c^2/h$ which is 1.25×10^{20}Hz and corresponds to a wavelength of 2.4×10^{-10}cm. The fascinating feature of annihilation is that it represents a perfect transformation from particles of matter (electrons) to electromagnetic waves (photons); there are no other ingredients required for this transformation, it is complete and perfect.

Pair production is the opposite process, the formation of an electron and positron from electromagnetic radiation. Curiously, the process is not quite the reciprocal of annihilation. Two photons do not combine to form the two particles, they are formed from a single photon of twice the annihilation frequency when the photon bumps into a catalyst, such as a heavy nucleus, which simply absorbs the excess momentum of the photon. This is really quite extraordinary. Imagine a super radio transmitter that will tune over the whole range of the electromagnetic spectrum. Starting at v.l.f. we tune it through the radio frequency band, the infra red band, the optical spectrum, the ultra violet spectrum, X rays and finally gamma rays. Nothing very remarkable happens throughout this whole range of frequencies until we reach a frequency of about 2.5×10^{20}Hz when – bingo! – two particles, a positron and an electron, appear before our eyes, formed only from the radio waves at that frequency – no pepper, no salt, no green cheese – just an electromagnetic wave and nothing else forming two particles of matter.

It is clear that, over three-quarters of a century after the discovery of the electron, no model had been suggested which could account for more than one or two of its many properties. Its greatest property had no quantitative explanation whatsoever, for its greatest property is its inertia and the only suggestion to explain this, that due to Ernst Mach, was entirely a qualitative hypothesis which could not account for the precise observations of inertial mass and inertial force.

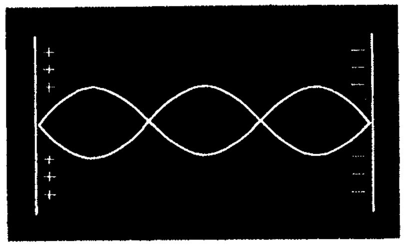


Fig. 1. *A simple phase-locked cavity with nodes at the end. The position of the boundaries in a phase-locked system is determined entirely by the wave system and not by rigid supports.*

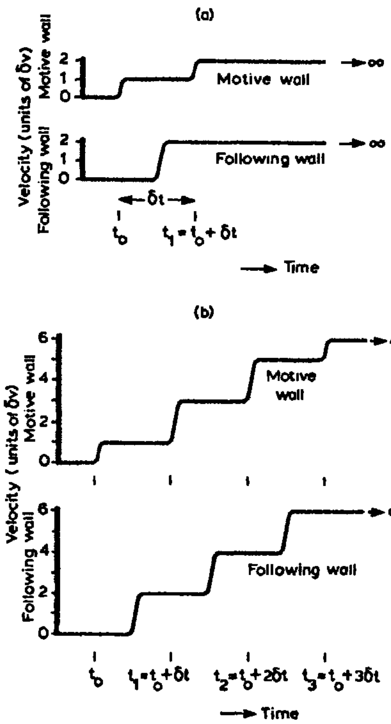


Fig. 2. *(a) The effect of maintaining a constant motive force for precisely the interval, δt, taken by the radiation to complete one round trip in a cavity such as that in Fig. 1. The cavity continues to move forward at a velocity 2δv. (b) The staircase of velocity produced by a motive force maintained constant for a time 3δt. In the limit, for a very large number of steps, the staircase approximates to classical linear acceleration.*

Phase-locked cavities

For about a decade a small research group at the Electronics Laboratory of the University of Kent had been trying to understand the electron, and, as a first step, they made it their job to clarify what happens when systems rotate. One might have expected that everything was known about rotating observers but this was far from the case. In the course of this research it was necessary to consider what happened to the units of length and time when they were accelerated, for only in this way could one express the measurements made by a rotating observer – everything that he measured had to be in terms of his local units. The question then arose that no one had solved the problem of the accelerated measuring rod; how did it maintain its length?

W. H. McCrea had gone part of the way towards the answer when he showed in 1952 that the rod would have to be made of a substance in which the velocity of sound was equal to the velocity of light. In a private conversation at a dinner in Oxford in 1972 he suggested that this might require impossible molecules but rejected the author's suggestion that the measuring rod would be simply a standing electromagnetic wave on the grounds that this would have no rest mass. I was concerned that McCrea's magic molecules could not be applied to the electron so I took up McCrea's challenge and within a few days I was able to show that a trapped standing wave not only had rest mass, it possessed the intrinsic property of inertia – once it had started moving it could only be stopped by applying a restraining force.

The physical mechanism is really very simple. Fig. 1 shows a macroscopic system in which a standing wave is trapped between two plates carrying equal and opposite charges of such a magnitude that they precisely balance the radiation pressure of the wave. If the left boundary is given a small velocity to the right, the wave reflected from it has a slightly higher energy and its wavelength is shorter. The shorter wavelength is reflected from the far end where it exerts a small excess pressure on the boundary, causing it to move to the right. The wave is then reflected back to the original end, closing the feedback loop; but a simple calculation shows that when it comes back from the moving boundary on the right it is redder and less energetic than the original wave in the cavity so that it *pulls* the left hand boundary. If the original motive force is now removed the whole system has no option but to continue moving to the right. It has gained energy relative to the laboratory but to an observer moving with it on the boundary it still has the original energy and original length, for it is still the same trapped standing wave. Thus the system has acquired inertia entirely from its own properties and without help from the distant masses of the universe. The effects of this are legion, for inertia affects our daily lives even more than gravity.

Newton's Second Law ($F = ma$) and also the Einstein relation $E = mc^2$ fall out from the above but it turns out that Newton's law is very slightly modified. The force has to be applied for the whole time that it takes for the excess radiation to complete the feedback loop, otherwise the excess is radiated back into space. Furthermore, if the push is applied for a considerably longer time the cavity accelerates by progressing up a 'staircase' of velocity (Fig. 2). It accelerates in little jerks because the transfer function of the system is, quite classically, quantised by the feedback loop and it acts as a simple integrator to attain the final velocity. If external radiation in the form of a c.w. signal falls upon a phase-locked cavity the delay in the feedback loop causes it to respond in the manner of the transducer in the "Radio waves or photons?" box and to register the quantum jumps of Fig. 2. Are the quantum jumps the right size? If the little cavity is filled with the electromagnetic wave that we associate with the annihilation of the electron, then the quantum jumps are precisely Planck's quantum of action. It looks as though, at last, we may be on the right track to solve the mystery of the electron. Are there any other idiosyncrasies of the electron that are shared by a phase-locked cavity?

Since the mid nineteen-twenties it has been known that the electron spins but that its angular momentum about its own axis is only half that to be expected from classical mechanics. Let us see if a phase-locked cavity exhibits the same feature. Fig. 1 shows that if we are to analyse a complete phase-locked cavity system then the total energy consists of the sum of the trapped wave energy and the potential energy required to hold the system together, i.e. the stored energy of the capacitor. The configuration shown in Fig. 1 cannot be applied to the electron, for the maximum of the electric field at the centre leads to severe difficulties if the system is rotated about the centre point. We therefore consider the 'push-pull' standing wave shown in Fig. 3. Let it be of unit cross-sectional area and let it be held together by a source of potential energy maintaining the dotted boundaries to either side. These boundaries may be formed quite naturally from spinning the system and we will not specify them further until we have completed our analysis.

Using similar units to Einstein (1905) the energy density of the travelling waves in the cavity at rest is $A^2/8\pi$ where A is the amplitude of either the electric or magnetic field. If the central node is caused to move, the energy density and the volume occupied by the wave system are both relativistically transformed. The cross-sectional area does not change but, as we are considering a phase-locked system, the length of the system to each side of the node is the effective length of the total travelling wave packet on each side.

We now consider that the central node is moved to the right at velocity v. Both of the component travelling waves to the right of the node have more energy and both of those to the left have less energy than when at rest since the boundaries at each end redirect the radiation within the time taken to complete the feedback loop. Thus the total energy E'_T of the system to an observer on the moving node is given by the transformed potential energy E'_p plus the transformed energy density times the transformed total wave length to the right, E'_{WR}, plus the transformed energy density times the total transformed wave length to the left, E'_{WL}:

$$E'_T = E'_P + E'_{WR} + E'_{WL}$$

$$= E'_P + \frac{A^2}{8\pi}\left(\frac{1+v/c}{1-v/c}\right)\frac{\lambda}{2}\left(\frac{1-v/c}{1+v/c}\right)^{1/2} +$$

$$\frac{A^2}{8\pi}\left(\frac{1-v/c}{1+v/c}\right)\frac{\lambda}{2}\left(\frac{1+v/c}{1-v/c}\right)^{1/2}$$

$$= E'_P + \frac{A^2\lambda}{16\pi}\left[\left(\frac{1+v/c}{1-v/c}\right)^{1/2} + \left(\frac{1-v/c}{1+v/c}\right)^{1/2}\right] \quad (1)$$

The radiation pressure (Einstein 1905) at the moving node from the wave system on the left is

$$P'_L = \frac{2A^2}{8\pi}\left(\frac{1-v/c}{1+v/c}\right)$$

and that from the wave system on the right is

$$P'_R = \frac{2A^2}{8\pi}\left(\frac{1+v/c}{1-v/c}\right)$$

The difference in these two expressions gives the force $\delta F'$ on the unit area at the node

$$\delta F' = \frac{A^2}{4\pi}\left(\frac{1+v/c}{1-v/c} - \frac{1-v/c}{1+v/c}\right) \quad (2)$$

From (1)

$$\frac{A^2}{4\pi} = \frac{4(E'_T - E'_P)}{\lambda\left[\left(\frac{1+v/c}{1-v/c}\right)^{1/2} + \left(\frac{1-v/c}{1+v/c}\right)^{1/2}\right]}$$

Therefore

$$\delta F^1 = \frac{4}{\lambda}\left(E'_T - E'_P\right)\left[\left(\frac{1+v/c}{1-v/c}\right)^{1/2} - \left(\frac{1-v/c}{1+v/c}\right)^{1/2}\right]$$

$$= \frac{8(E'_T - E'_P)}{\lambda(1-v^2/c^2)^{1/2}} \cdot \frac{v}{c} \quad (3)$$

We may replace λ by $2c\delta t$ where δt is the time taken by a wave to complete the feedback loop by travelling out from the node and back again.

The force that we have established is of enormous magnitude, even at 1 metre per second when v^2/c^2 is only 10^{-17}, so we may drop the expression $(1-v^2/c^2)^{1/2}$ and state to first order

$$\delta F = \frac{2}{c^2}(E_T - E_P) \cdot \frac{2v}{\delta t}$$

But $2v/\delta t$ is the acceleration over a complete feedback cycle, hence

$$\delta F = \frac{2}{c^2}(E_T - E_P) \cdot a \quad (4)$$

But, in the rest state, the wave energy equals the binding energy and they together comprise the total energy, hence

$$\delta F = \frac{E_T}{c^2} \cdot a = m_o a. \quad (5)$$

Thus we derive Newton's Second Law and $E = m_o c^2$ at the same time. It would have been possible to derive these relations quite simply by ignoring the second order terms at the outset, but this analysis is enlightening in that eq. (4) shows that only half of the total energy comprising the inertial mass contributes actively to the inertial force. The law of inertia would be twice as efficient ($\delta F = 2m_o a$) if the potential energy also contributed to the inertial force of a phase-locked cavity, i.e. if the transformation of E_P had a first order component. Thus if a particle is formed entirely from an electromagnetic wave, half of the wave system actively produces the inertial phenomenon, whilst the other half is equally essential but plays a passive role. Once a complete particle has been formed as a phase-locked system, it can interact with external forces completely in accordance with the laws of mechanics; in particular, its total mass is available to produce reaction to an impressed force. In contrast, if we apply the inertial laws *within* a closed loop wave packet then we do not have a situation where the waves act on existing particles and we may only employ half of the wave energy in establishing the active component.

Thus, for entirely classical reasons, some laws of mechanics break down when applied *within* elementary phase-locked systems though they are perfectly valid for the external behaviour of the complete systems. The concept of moment of inertia is based upon the concept of inertial mass as it appears in Newton's law. If the concept is applied internally to a rotating phase-locked cavity, then only half of the energy is actively operational, thus: *The moment of inertia of a phase-locked cavity about its own axis is half that which is given by the classical mechanics of an externally equivalent system composed of particulate component masses.*

If we identify an electron with a phase-locked cavity formed entirely from electromagnetic waves and we wish to establish its internal angular momentum, then we must reserve half of the total internal energy for the passive role so that the internal angular momentum is therefore only half that which would be given by considering the total energy of the system.

It is suggested that this is the classical origin of the (anomalous) spin angular momentum of the electron and other fundamental particles. Furthermore, a comparison of the magnetic moment of an electron with its internal angular momentum should give a value which is twice that observable for the behaviour of the complete phase-locked particle in motion around a distant nucleus. It is suggested that this is the origin of the anomalous magnetic moment of the electron.

Apart from accounting for the enormous forces of inertia which affect our daily lives, the analysis shows that the principle of the phase-locked cavity

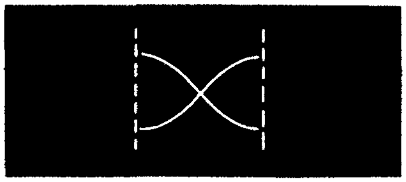
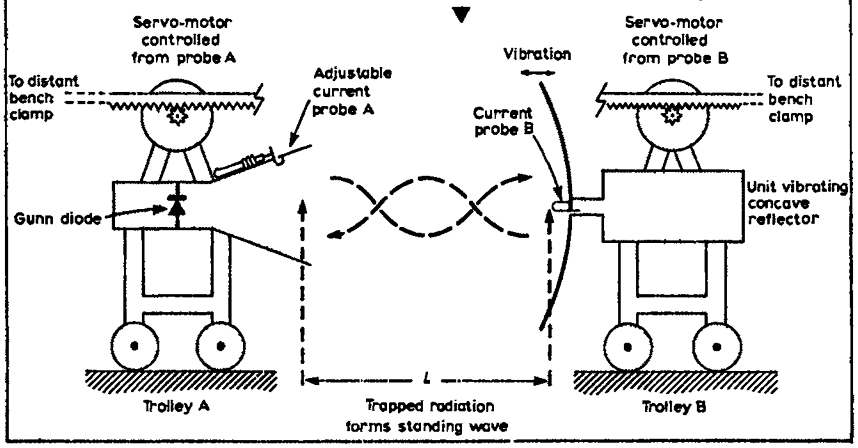


Fig. 3. *A λ/2 standing wave with zero electric field at the centre. An electron may consist of two such systems at right angles rotating about the central node.*

Fig. 4. *The freely floating phase-locked cavity. The distance L is maintained constant by independent sensing and control on each trolley. This effectively amplifies the very weak control exerted by the normal boundary conditions although the speed of response is degraded. The independent trolleys accelerate and move as though they were a single solid body upon the application of a horizontal force applied to one trolley only. Upon removal of the force the system coasts at the terminal velocity, still maintaining L constant.*



appears to reconcile many of the differences between the classical and quantum behaviour of matter. A phase-locked cavity has a transfer function which reproduces the quantised relationship between an external influence and an elementary mass; furthermore it has an anomalous equivalent mass for the application of the classical laws of mechanics to its internal properties. In particular, if one accepts that there is a unique wavelength (the Compton Wavelength) at which electromagnetic waves can lock into a closed loop system, then a particle can be formed which has all the following properties of an electron: inertia; quantised transfer function; rest mass; angular momentum (half classical); electric field equivalent to a localised charge; magnetic moment (including the anomaly); preservation of the proper units of length and time when accelerated to a different frame; indeterminacy arising from lack of knowledge of the phase of the internal waves.

We cannot, of course, see an electron. Any attempt to do so causes the electron to move smartly out of the way in accordance with the principles that we have just established, but we can, on the basis of this analysis, set up a model which would have the required characteristics. This tentative model would consist of two spinning standing waves, somewhat like that in Fig. 3, set at right angles and electrically in phase quadrature. Preliminary investigations suggest that relativistic aberration renders this system equivalent to two travelling wave systems of double the frequency rotating in an annular manner around the centre as seen from the laboratory. The electric fields of the waves would give a static but spinning electric field pointing either inwards or outwards according to the sense of rotation, and the magnetic fields of the waves combine to form a dipole field through the centre.

At the moment we need just one postulate to apply a model such as this, that, at the annihilation wavelength, nature permits such a configuration to lock in perfect equilibrium. This one postulate then dispenses with all the separate postulates required for other descriptions of the electron, inertia and the quantum theory. What does this tell us about the photon concept? A phase-locked cavity will respond in a quantised manner to either a short train of waves or a continuous signal but, when it surrenders its excess energy, this appears in simple short wave trains of radiation which may then mix with other free wave trains perfectly in accordance with the superposition property of Fourier theory. The photon is quite classical!

Is it possible to make a macroscopic phase-locked cavity? We have made two in the Electronics Laboratories at the University of Kent, one using laser light and the other using radio waves. The radio wave version is shown in Fig. 4. Though this is by no means a perfect analogue, it clearly demonstrates a system which maintains the same number of wavelengths between the boundaries. With care it may be set up so that the frictional losses are cancelled and a slight push at one end then causes the two trolleys to move freely as a single particle. Small noise perturbations are rather amusing for they cause the system to have a mind of its own and to perform unpredictable little dances in the manner of one-dimensional macroscopic Brownian motion. It is possible to make this system from a cheap intruder alarm Gunn diode assembly feeding the horn on the left and a 2½ inch loudspeaker carrying the reflector on the right. A tiny two-turn loop in the plane of the reflector feeds a crystal diode, the output of which goes to an audio amplifier, synchronous detector and power amplifier feeding a small motor on the same trolley. A similar arrangement is associated with a crystal diode and detector loop mounted through the wall of the horn on the left trolley and it is advisable to include an isolator or attenuator between the Gunn diode assembly and the horn in order to reduce pulling of the oscillator by the reflector on the opposite trolley. The loudspeaker is driven with a very small amplitude at about 120Hz and the synchronous detectors are referenced to the same 120Hz source.

It is possible to construct analogues of many aspects of this work but demonstrations of inertia are all around us. The next time you stub your toe or hold on to your seat belt remember to blame all the little feedback loops forming your elementary particles. Without feedback none of this would be possible; if we could form a stable self-contained particle entirely from static fields we might be able to have energy without inertia but there would be no phase-locking principle to regulate its size and give it quantisation. Would it also defy gravity? This analysis is reassuring in that it preserves Einstein's Principle of Equivalence and does not reduce it to a Principle of Identity between gravitational and inertial forces.

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