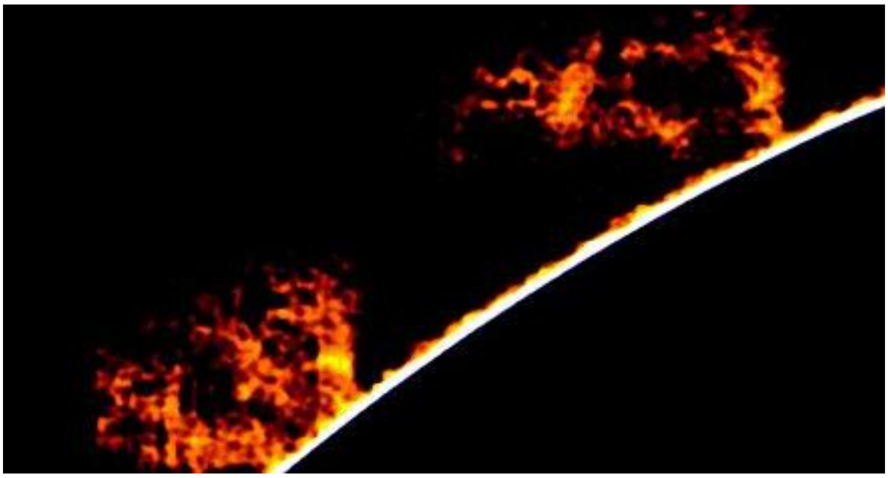

Virtual and real photons

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ABSTRACT

Maxwell did not believe in photons. However, his equations lead to electro-magnetic field structures that are considered to be photonic by Quantum ElectroDynamics (QED). They are complete, relativistically correct, and unchallenged after nearly 150 years. However, even though his far-field solution has been considered as the basis for photons, as they stand and are interpreted, they are better fitted to the concept of virtual rather than to real photons. Comparison between static-charge fields, near-field coupling, and photonic radiation will be made and the distinctions identified. The question of similarities in, and differences between, the two will be addressed.

Implied assumptions in Feynman's "Lectures" could lead one to believe that he had provided a general classical electrodynamics proof that an orbital electron must radiate. While his derivation is correct, two of the conditions defined do not always apply in this case. As a result, the potential for misinterpretation of his proof (as he himself did earlier) for this particular case has some interesting implications. He did not make the distinction between radiation from a bound electron driven by an external alternating field and one falling into a nuclear-Coulomb potential well. Similar failures lead to misinterpretation of the differences between virtual and real photons.

Keywords: Far-field radiation, Coulomb potential, non-photonic radiation, virtual photons,

1. BACKGROUND

Since first using Feynman's Lectures[1] over 45 years ago to study for my PhD qualifying exams, I have used these 3 volumes more than almost any of my other physics textbooks. I have often challenged his statements or proofs and, nearly as often, been amply rewarded for the effort of proving myself wrong. In recent years, I have had the opportunity to study these volumes even more. Therefore, when presented with the challenge to find out why ground-state electrons do not radiate, despite their being accelerated charges, it was natural for me to turn to Feynman first. While I have not yet fully answered my question, some interesting observations have come to light.

Feynman presents his case for radiation from accelerated charges in both Volumes 1 (chapter 28 "Electromagnetic Radiation") and 2 (chapter 21 "Solutions of Maxwell's Equations…"). I will assume that the reader has access to these volumes and I will therefore only give a brief overview and then more detailed comments on the pertinent points. In Volume 1, he gives the classical equation (1) for the electric field **E** (at point 1) from an arbitrarily-moving point charge (at point 2).

$$\mathbf{E} = \frac{-q}{4\pi\varepsilon_o}\left[-\frac{\bar{e}_{r'}}{r'^2} + \frac{r'}{c}\frac{d}{dt}\left(\frac{\bar{e}_{r'}}{r'^2}\right) + \frac{1}{c^2}\frac{d^2}{dt^2}\bar{e}_{r'}\right] \tag{1}$$

In this equation, r' is the distance between the two points at time t and $\mathbf{e}_{r'}$ is the unit vector in that direction. The prime (') is used to denote the fact that the source terms must be evaluated at the "retarded" time t' and place (e.g., x', y', and z'). These are the time and place of the source when the field was generated, rather than the x, y, z, and t at the field-measurement point (in space and time). This has important consequences for the discussion below.

The important term in (1) for radiation is the last one, which contains the second time derivative of the unit vector. While Feynman does not prove this in Volume 1, he does describe the physics of the terms and the basis for stating that this 3rd term, rather than the other terms, gives the far-field radiation contribution (attributed to an inverse-distance, 1/r', rather than an inverse-square, $1/r'^2$, dependence). As usual, he is careful to give the assumptions and conditions under which his derivations are valid. In this case, the explicit assumptions are:

a) small displacement **d** of source;
b) non-relativistic velocity of source;
c) field point a long distance from source (so that $r = r_{12} = r'$); and
d) use of retarded effects between the source of field and measurement points.

Feynman gives, without proof, a "rule" for getting the electric-field components (2) in terms of acceleration (e.g., a_x) and inverse distance (1/r) of the source relative to the field point.

$$\mathbf{E} = \frac{-q}{4\pi\varepsilon_o c^2 r} a_x\left(t - \frac{r}{c}\right) \tag{2}$$

The generalized version of equation 2 is declared [I 28-3] to be the central "law" for understanding "all of the phenomena of light and radio propagation." Feynman then proceeds to give two physical (non-mathematical) examples to demonstrate the application and generality of this radiation term and leaves the details of a proof until Volume 2.

In Volume 2, after having taught about Maxwell's equations and the vector potential **A**, Feynman returns to these equations. In section II 21-4 ("The fields of an oscillating dipole"), he finally derives the admittedly difficult details of equation 2 and starts the section stating that his equations "are equivalent" to the many other forms of the field equations for, and radiation power from,[2] a moving charge.

Starting with a "charge pair" (a dipole), he develops an expression for the **B** field far from an oscillating dipole and, with inclusion of the retarded effects shows the determination of the 1/r dependence of the radiation field. An important point for the student is Feynman's attempt to show the physical basis for this, rather than for the expected $1/r^2$ dependence. Ultimately, my contemplation of this description led to the recognition of his implied assumptions.

2. IMPLIED ASSUMPTIONS FOR FEYNMAN'S PHOTON DERIVATION

There are at least two assumptions in the derivation that are not explicitly stated there:

1. Relative motion of dipole charges is that of a simple harmonic oscillator (SHO).
2. The dipole oscillation is maintained, over 'sufficient' time, along a single axis, to form a photon.

Both of these implied assumptions are couched in the description of the dipole moment by: $p = p_z = p_o\sin(\omega t)$. What is the basis for these assumptions and what are the implications for the proof? Another assumption, based on assumption 'b' above (non-relativistic motions), leads to:

3. Radiation moves out radially from a source, rather than along field lines.

Feynman's basis for assumption 1 is found in Volume 1 (I 31.2, "The field due to a material"), wherein he states "The correct picture of an atom, which is given by the theory of wave mechanics, says that, *so far as problems involving light are concerned*, the electrons behave as though they were held by springs." Without a detailed search of the volumes, I believe that he adheres to this view in all cases, except in the derivation of the hydrogen-atom energy states (Volume 3, chapter 19), where he uses the correct inverse-r Coulomb potential).

The basis for Feynman's statement is that most problems regarding light, described in his lectures and in physics in general, are for forced oscillations. With an external "driver," the assumption of a linear simple-harmonic oscillator is the easiest (and perhaps the most common and correct) functional dependence. Therefore, the resulting perturbation of the electron's orbit, or path, is also harmonic and linear, with the restoring force proportional to the displacement from the equilibrium. However, when the electron motion is defined by its own energy and momentum in the presence of the strong central potential of the nuclear charge, rather than in a weak external field (relative to the Coulomb near-field of the nucleus), things are different. The motion, while small relative to the distance at which the field is measured (and consistent with Feynman's 1st explicit assumption 'a'), is large relative to that of most forced oscillations. Furthermore, it is not constrained to a single axis or even a plane. Thus, for radiation from decay of an externally-unperturbed orbital electron, Feynman's stated assumptions are insufficient and the implied assumptions are incorrect (Appendix A).

2.1 Implications of Implied Assumption 1

With a driven simple-harmonic oscillation (**a** = k•d), the acceleration in (2) is greatest when the dipole charges are furthest apart (hence, at point of largest dipole moment). Thus, the radiated field is greatest at this point and particularly large because the acceleration and dipole moment are largest at the same time. The radiated field reflects the nature of the SHO driver. On the other hand, with an unperturbed electron, the radiated field depends only on the orbit and may be quite different. For a circular electron orbit (which Feynman describes as "just an oversimplified picture," I 31-2), the conditions are that of a SHO and his model is still valid.

For a "linear" electron orbit, such as Feynman describes mathematically in his derivation of the hydrogen s-orbital energies for electrons without angular momentum (III, 19-2), things are quite different. The acceleration for an electron in the center (i.e., as d --> 0) of a 1/d potential is extreme (but not infinite[3] see below, and the subject for another paper), however, the dipole moment (qd) approaches zero at this point. Furthermore, the acceleration direction reverses as the electron passes through, or by, the nucleus. Thus, instead of a SHO radiated field, an s-orbital electron produces an extremely-sharp (in time and space), bipolar (or even tri-polar), pulse twice (or perhaps once, as seen from a single point) every cycle. The amplitude and shape of the radiated field prediction depends on the models used for the nuclear and electron charge distributions.

In this section, we will examine the differences between far-field radiation from a SHO electron (e.g., a circular orbit) and an electron with a near linear orbit in a Coulomb potential (s-orbital). In a later section, we will relax the assumption of a stable axis of motion. Figure 1 compares the maximal electric far-fields, based on eq. 2, for the SHO charge and the Coulomb potential (E2 and E2' respectively at an identical, but arbitrary, distance r from the charges) as functions of position in the oscillation cycle. The examples are the extreme of the hydrogen ground-state orbital. It is clear that there are many orders-of-magnitude difference between the extreme intensities of the fields from the two models.

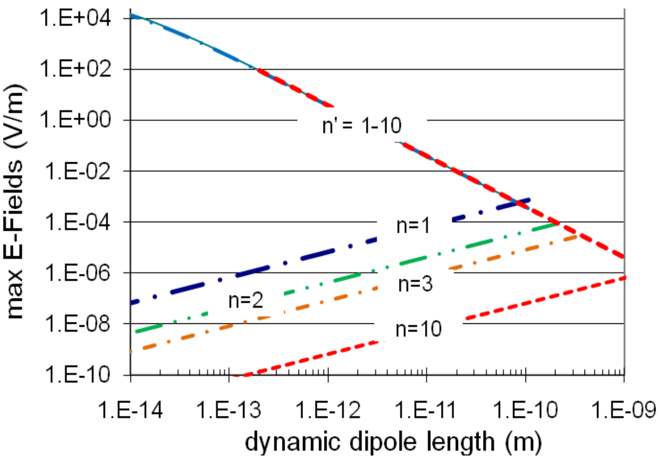

Figure 1. Maximum electric-field strengths for a simple-harmonic-oscillator charge dipole (n = 1, 2, 3, & 10) and for an electron in a Coulomb potential (s-orbits, n' = 1 - 10) as functions of position in the oscillation cycle (dipole length).

The maximum electric fields radiated from s-orbitals (Coulomb field) are compared to those far fields from circular orbitals or from SHOs. The field strengths (in units of volts/meter) are all calculated for a distance from source to measurement point of r = 1 meter. The maximum field is measured at a point perpendicular to acceleration of the instantaneously-linear motion of the SHO (or of a linear motion of the s-orbital) at the time of emission (retarded time). Comparison is made for several different orbitals (n and n' = 1, 2, 3, and 10) to show the effects of electron-orbital frequency and amplitude of displacement.

The dipole length, d, extends from near-nuclear diameters (> 10^{-15} m) to beyond the equilibrium orbital radii (~ 10^{-10} m). The fields from electrons in simple harmonic motion increase in amplitude with d and decrease in amplitude with increasing orbit number (n' = 1 - 10). The higher-n orbits also extend to greater dipole lengths. The fields from the electron in a Coulomb potential follow the same curve regardless of the orbit number (n' = 1 - 10). The higher orbits simply extend to greater dipole lengths. As expected, the n' curve on the log-log plot displays a $1/d^2$ dependence.

Comparison of the electric-field strengths, as a function of the oscillating dipole length for the two oscillator types, indicates the location of the maxima and the ~ 8 orders-of-magnitude difference resulting from their relative accelerations. The difference in field amplitude would be even greater had I extended the point particle model into the nucleus and not put a limiting term into the Coulomb potential.[a] This term prevents the singularity of a point charge at the origin and gives the slight curvature seen in the top of the n'=1 curve.

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[a] I use Feynman (I 28-2) for the field from a SHO charge, with the acceleration a_x used in his equation 28.6 coming from the discussion in II 21-4, with equation 21.22 for the far-field B-field and the last term in 21.26 for the E-field). For the Coulomb potential, the equation to determine the field is the same. The difference is in the acceleration dependence on d. In the following

Another feature in the figure is the differences between the oscillator types in the displayed orbits. The multiple field 'paths' for the SHO, as mentioned below, indicates a failure mode for this model input. The Coulomb potential gives equal accelerations for same electron positions.

3. 'RADIATED' FIELDS

The amount (field amplitudes and energy flux) and meaning of radiation from a bound electron is a more detailed problem. As applied to photons, they are not that predicted by an uninformed user of Feynman's (and, by extension, all 'claimed' classical) radiation analysis. We can now examine the consequences of the non-SHO nature of the atomic electrons as a radiation source.

When the radiated **E**-fields are plotted against time rather than dipole length (Figure 2), the differences are even more striking. Time in the figure is plotted for ½ cycle; from one extreme to the other. The 2nd ½ cycle retraces the first. While it is clear that the radiation emitted from a SHO electron is a sinusoid (Xs), the field from an electron in a Coulomb potential (dashed curves) is a completely different creature. In this diagram (and in this section), we have assumed that the electron transits the nucleus unperturbed (zero **E**-field in the center of the plot). In the SHO case, where forces are nearly zero at the nucleus, this is a valid assumption. In the Coulomb potential, where the electron is relativistic as it approaches the nucleus and the potential is no longer proportional to 1/d, this assumption is clearly invalid (to be explored later).

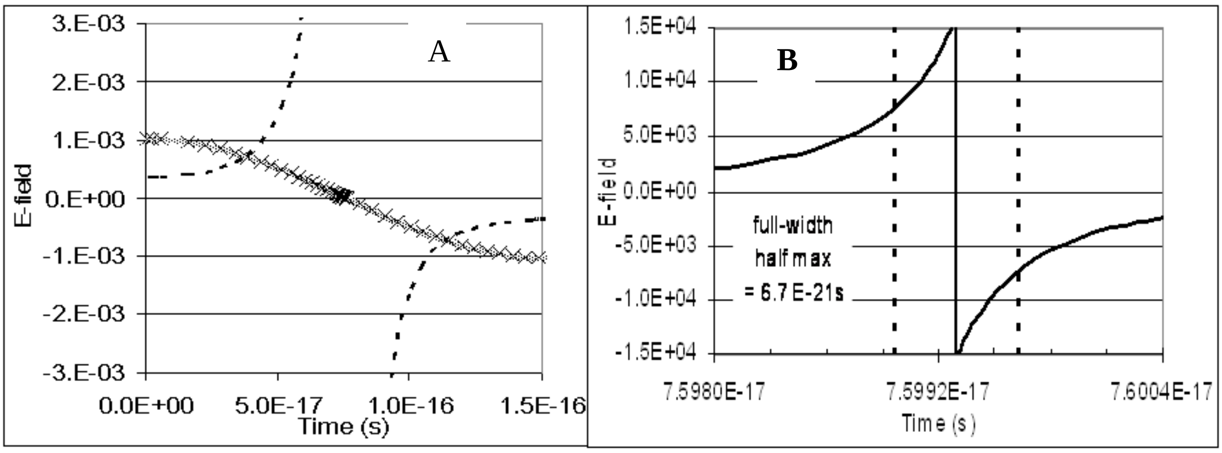

Figure 2. (A) E-fields radiated from a SHO (speckled pattern) and from a Coulomb potential (dashed curves) plotted as a function of the time between the extreme dipole lengths. A cosine curve (Xs) is superimposed to show the SHO nature of the radiated field. (B) plotted as a function of the sub-attosecond time at closest approach. Note change in time and field scales between (A) and (B)

A closer look at the **E**-field radiated from an electron in a Coulomb potential. **E**, plotted as a function of the time for the $2.4\mathrm{x}10^{-20}$s about closest approach of the electron to the nucleus (Fig. 2(B)), gives an even better perspective on the problem. This radiation is an extremely-fast, very-intense electro-magnetic pulse occurring about every 1/10th of a femtosecond. The 50% points between the positive- and negative-going radiation pulses (as the electron transits the nucleus) are separated by less than $7\mathrm{x}10^{-21}$ seconds. Note that the field strength exceeds $\pm 1.5\mathrm{x}10^{4}$ V/m at 1 meter from the radiating dipole. It is definitely not SHO and it does not look like proper starting material for a photon! We must assume that, based on Maxwell's equations, there is radiation of some sort. It just might not be photonic radiation.

3.1 Implications of Implied Assumption 2

An s-orbital electron has no net angular momentum (based on the Heisenberg Uncertainty Principle, it can have non-zero instantaneous values)[4] and it has an isotropic probability distribution about (and within) the nucleus. While quantum mechanics would say that it has no observable orbital nature (and thus this radiation analysis might have no meaning), classical dynamics would say that the s-orbit electron spends a portion of its time near or inside the nuclear potential well and generates its maximum magnetic and electric fields as it passes through this region. The electron orbit (near-linear) is therefore systematically and randomly perturbed as it transits this highly-energetic

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calculations, I have used a_x **F**/m = $q^2/4\pi\varepsilon_o c^2 d'^2$ m , where d' = d + $2d_n$ and d_n = ~ twice the proton radius. This additional term in the distance between electron and proton prevents the singularity and the infinite field from the mathematics of point charges.

strong-field nuclear region. The random perturbation of a near-linear orbit, integrated over time, results in the isotropic distribution of an s-orbit electron. What does it do to the predicted radiation field from the accelerated electron?

In addition to the greatly increased maximum **E**-field from electrons in a Coulomb, relative to a SHO potential, there is the problem of repetition. While the frequency of an electron in a "stable" s-orbit will remain constant, the direction of maximum radiation will constantly change. The assumptions of integration over closed paths and identical orbits require closed cycles. This does not occur often in a randomly changing orbit. However, if reduced to a one-dimensional problem, this works.

The 1/r dependence of the fields, which is claimed to be critical to the radiation effect because of the requirement for the energy content of an outgoing wave to have a $1/r^2$ dependence (I 29-2), is violated by radiation from some undriven electrons in atomic orbitals.[5] Does this mean that there won't be any far-field radiation? Since the outgoing power (Poynting vector) depends on **E**x**B**, it doesn't care about field reversals (since **E** and **B** reverse at the same time). Thus, while there can be no consistent far-field coherent radiation from an s-orbital electron, the radiation equations say that there would <u>still</u> be a power flow. What does this mean? How is it to be treated?

The violation of Feynman's implicit assumptions might be reduced, if we are able to "average" over hundreds of thousands of cycles or to average over proximate collections of similar numbers of identical radiating dipoles. Nevertheless, the energy density radiated from this fixed-period, but otherwise random, oscillation of fields from a single dipole should rapidly approach the zero-point-fluctuations level of space and could possibly be treated by stochastic electrodynamics (SED).[6] The radiation from a large collection of dipoles is a different story and is the basis for classical electrodynamics for which these equations do hold.

What is this radiation from a single electron and what in nature responds to it, and how? That is the subject for another paper, as are the implications for radiation from higher-atomic-number s-state orbitals. A Fourier decomposition of this waveform is rich in ultra-high frequencies. The fundamental for the majority of the energy of this radiation pulse, for even the hydrogen atom (at ~10^{20} Hz), would be in the gamma-ray region; but, if it can maintain alignment, it happens about 7 x10^{16} times/s.

Only if, without interruption or deviation, the electron can follow this path about a million times could sufficient energy accumulate to form a multi-eV photon. Statistically, this might happen. However, there is another hint about how photonic radiation can be obtained from such electron motion. Photons have angular momentum ($L = \hbar$). Therefore, to form such a form of radiation, an s-orbit electron must change to an orbit with angular momentum. Similarly, an s-orbit electron can form from an electron in an orbit with $L = \hbar$. Thus, to form a photon, something must 'happen' to alter this electron path to or from a linear-electron orbit.

4. VIRTUAL PHOTONS

There are problems in the description of photonic radiation from a simple harmonic oscillator. Feynman's classical derivation says that a bound electron must radiate until there is no longer any energy available – or until the conditions change. Is this derivation incorrect (see Appendix A) and quantum mechanical magic is the only answer? Or, is there just more to the story?

A virtual photon, like a virtual particle, represents an energy source and therefore a force. What is it and how does it work? We have seen how the bound electron radiates EM energy into the near field. This is equivalent to an evanescent wave. It has energy, but does not leave its source. Thus, it does not convey energy until an appropriate absorber is present. However, it can incorporate other bodies into its energy 'pattern'. In doing so, it seeks the lowest level and presents a 'force' to get there ($F = -dV/dx$). The energy field depends on many things. However, the Yukawa potential seems to fit the pattern very well. It provides a representation of the short-range nuclear forces by virtual, massive, particles on one extreme and long-range (infinite) Coulomb forces by virtual, massless, photons on the other.

If sufficient energy is available, then actual energy transfer can occur and a real particle or photon can become evident. Otherwise, there is generally a random exchange of energy and no real change of state results. This exchange is described in terms of a resonant-oscillation frequency. Why do the characteristic interaction ranges of evanescent waves or virtual particles reflect specific masses? Are there only specific resonances that can exist within various potential wells? Why does a characteristic mass (e.g., a pion) provide a specific range; but, energy-without-mass (i.e., a photon) has no such limitation?

Physics is a study of resonances. Resonances are characterized by a frequency; but, often they appear as wavelengths based on the frequencies. The atomic-electron orbitals are resonances of the electrons in a Coulomb potential well. The deBroglie wavelength of a particle is a resonance between its relativistic motion (velocity and/or momentum) and an internal 'nature', e.g., the Compton wavelength. The Compton wavelength of a particle is a resonance associated with its mass and energy related to a motion at the velocity of light. Photons have characteristic resonances between the EM fields and the medium in which they exist. Conditions under which more than one resonance coincide provide particularly stable points. Do virtual particles or photons have such resonances or simply reflect their existence in the real version? Since they have no mass and no stable energy, they have no resonances of their own. Thus, virtual particles reflect the resonance conditions of their source.

We have proposed that the atomic electrons create resonance conditions required to form real photons. Almost all of those same conditions exist even when real photons cannot be created. Real photons can transfer energy over vast distances. If the Coulomb field is expressed in terms of virtual photons then, in theory, they also can have infinite range. However, this fits with the distinction that I have drawn between Maxwell's far-field radiation and photons.[5] Real photons, as solitons, are independent of their source and virtual photons, as standing waves, are not. Virtual photons thus have the source resonance, but not the photon resonance ($E = h\nu$, which leads to an angular momentum of $\hbar$) needed to become real. This line of reasoning can be extended to other virtual particles and perhaps identify the nature of some of their sources.

There is another difference between virtual and real photons. Photonic radiation obeys the black-body spectral limitations. As indicated above, the EM far-field radiation has most of its energy, as described by a Fourier decomposition of its frequency content, far beyond that possible for black-body radiation even at solar temperatures. This 'non-photonic' radiation, obeying Maxwell's laws, also perhaps follows more closely the Rayleigh-Jeans law.

5. FURTHER IMPLICATIONS AND CONCLUSION

None of these atomic-electron radiation models adequately addresses the measured, monoenergetic, photons from undriven electrons in excited, or even unexcited, states. These photons are individually emitted with a probability distribution in time and direction, but are not likely to coalesce or precipitate from a diffuse energy cloud that is moving out in all/many directions from a source region at the speed of light. They just do not have the time. Furthermore, how does the angular momentum required for a photon get from the electron (and from where else could it come in a radially symmetric field).

The more likely source of photons is the high-density, near-field EM energy (generated by the $1/r^2$ terms of the field equations) that is intimately coupled to the electron for long periods. Since individual photons are not bound by the $1/r^2$ energy dependence, there is no reason to tie them (even by implication, as I did when starting this paper) to the far-field radiation term. Their consideration may not directly answer the question of the far-field, non-photonic, radiation from undriven bound electrons. However, in a manner similar to that of photon formation, the interaction of the near-field energies with the accelerating electron(s) could perhaps provide the answer in the form of a 'cancelling' or 'counter' field (not provided for in the equations).

The detailed study of photons[7] appeared to have been sidetracked for many decades by the advent of quantum mechanics and QED. I believe that it is overdue for a revival. A study of the formation of photons from an excited atom, relative to the scattering of photons from an externally-driven ensemble of atoms, appears to be a good starting point (Appendix). Recognition of the differences between the SHO and the 1/d central-potential models, as spelled out above, is critical.

An important distinction not yet made has to do with the frequencies used in the appendix calculations. First, a SHO may gain or lose energy without changing its frequency. An electron in a 1/d-potential cannot do so. Its frequency increases as it loses potential energy. This distinction invalidates Feynman's 'proof' that far-field radiation from an atom is not 'bound'. However, it may prove that any such unbound radiation must be photonic (i.e., not spreading in space).

Another point, which Feynman apparently overlooks, is the fact that the frequency of radiation, in atomic decay, is not the frequency of the orbiting electrons. In I 32-3, he states explicitly that the natural frequency, i.e., the SHO frequency of the electron is the frequency at which the atom is radiating. If defined properly, this might be correct. However, he had described the simple-harmonic-oscillator frequency earlier in the section as that of "an electron in an atom." In a later paragraph, he gives an example of radiative decay of the sodium atom. While his numbers are reasonable (and I've used them for years), his method is wrong! The natural frequency is the unique resonant(s) of the electron and photon system. He does not mention this; nor does he include the photon in the Hamiltonian of the hydrogen atom when he carries out that calculation (using a Coulomb potential).

Nearly 50 years ago, when Feynman presented his lectures, there were many unanswered questions that he was willing to talk about. Most of them have not yet been answered (or the answers have not been accepted) despite the gains in so many areas of physics. I fear that in most cases, this is a result of a fear of "wasting" time on problems that the great minds in physics could not solve in the past. As I have gotten older, I recognize that even though they may not have "solved" the problems, there is much "gold to be mined" in their thoughts, books, and presented papers. And, even in some cases, views of the 'losers' in the big battles over the 'proper' theories could still be vindicated.

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APPENDIX: Did Feynman really prove that classical electrodynamics predicts no photonic radiation from the orbital decay of some atomic electrons?

Answer? Not really! But, his proof, that far-field radiation (i.e., photons) depends on a constant-frequency source, is violated by the radiative decay of excited atoms.

In his "Lectures," Feynman provides a classical proof that an electron in simple harmonic motion radiates. By extension of his method, he therefore proves that orbital decay of some atomically-bound electrons, which obey the Coulomb potential rather than simple harmonic motion, does not produce far-field photonic radiation as claimed. This hidden proof is based on the fact that a classical decaying orbit increases in frequency with time. The reality of radiative decay is much more complicated than suggested by the radiation term of the classical equations (or by quantum mechanics).

There are reasons given in this paper not to believe that photons from decaying atomic electrons are produced by the "acceleration" term in the classical electric-field equation (eq. 1).[a] Nevertheless, the fact of radiation (and of radiation in the form of photons) from accelerated charge is indisputable. The point of distinction here (and one that Feynman did not make in his "Lectures on Physics")[1] is that of photonic vs non-photonic radiation. Thus, while there is no doubt about accelerated charges producing radiation, there is a question about whether they must produce photonic radiation. Furthermore, in his "proof" that charges (as simple harmonic oscillators, SHOs) radiate via their acceleration, Feynman provides the basis for a proof that those decaying-orbit electrons, which deviate significantly from simple harmonic motion, cannot radiate via the far-field mode.

In his "Lectures on Physics," Feynman provides a classical demonstration or argument[b] that an electron in simple harmonic motion radiates and radiates electromagnetic energy over great distances. He does this neatly by showing that "the variations *with time* at the source are translated into variations *in space* as the waves are propagated outward..."

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[a] We are basing this discussion on Feynman's Lectures,[1] primarily in Volume 2, 21.1-4.

[b] Whether or not this argument can be classified as a proof is left to the purists.

One of the implicit assumptions in his discussion of radiation is that the motion of the electron is simple harmonic.[c] Another is that the "natural" frequency[d] of the electron is that of the radiated photon[e]. The result of these assumptions is that, by assuming the system[f] to be a simple harmonic oscillator (SHO), a fixed frequency, ω_o, can be assigned for the constant total energy. This fixed oscillator frequency is a requirement for Feynman's proof that an accelerated electron radiates. Violation of this condition is the basis of his hidden proof that atomic electrons do not radiate when changing orbits.

In a nutshell, Feynman's argument states that the electric-field strength, measured far from an accelerated electron, depends on the acceleration (in eq. 2, and the 3rd term in RHS of eq. 1)[g] and falls off as 1/r', where r' is the distance from the electron (radiating at time t_1) to the measurement point at time t_2.[a] Since the electron is an oscillator, the field varies with time as it radiates out from the source. Because of the electron motion, it is necessary to use the value (magnitude and direction) of **r'** from the point at which the radiation originated at t_1. As a consequence, the field strength, and its gradients, depend on both location and time, and not independently. The spatial gradient of the field at a given time and place depends on the amplitude of the outgoing wave at that *location. The amplitude of the envelope of the field wave varies as* 1/r',[h] therefore the gradient of the field does as well (Figure A-1A). The radiated power from the accelerated charge, the SHO, then falls off as $1/r'^2$ (the Poynting vector is proportional to the fields squared) and moves out as a non-decaying locally-spherical wave.

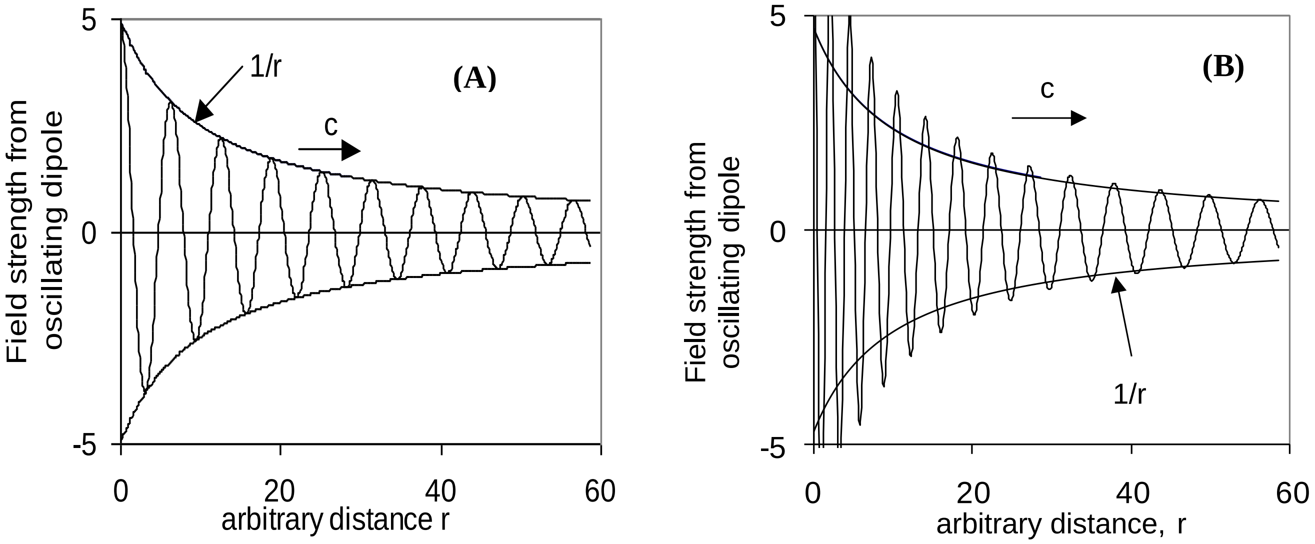

Figure A-1. Electric-field-strength (and a 1/r envelope) far from (A) a charged SHO and (B) a decaying-orbital electron .

By implication, and extension of his method, Feynman therefore proves that orbital decay of an atomically-bound, near-ground-state, electron, which obeys the Coulomb potential (and does not display simple harmonic motion), does not produce far-field radiation as claimed for an accelerating charge. This hidden proof is based on the fact that the frequency of, and radiation-field amplitude from, a classical electron in a decaying orbit increases with time. As a consequence, during the decay process in which the electron spirals in toward the nucleus to a lower orbit, the wave amplitude of the radiation train gets larger and larger and the peak–to-peak spacing becomes more and more

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[c] See section 2 in the text.

[d] The use of "…the frequency at which our atom is radiating …" comes from an example given in his section on radiation damping (Volume 1, section 32-3). The problem that a highly-excited electron can decay and radiate from many levels, and thus have many such natural frequencies, is not really addressed. The mass used in the SHO is that of the radiating electron.

[e] The assumption that the radiation is photonic comes from an example also given in his section on radiation damping (Volume 1, 32-3). His identification of emitted and measured sodium light of a given wavelength with photonic radiation is assumed by the present author. See if you don't agree. Quoting Feynman, "Now let us actually calculate the Q of an atom that is emitting light…"

[f] It is possible that, in these assumptions, he meant that the motion of the electron plus photon is simple harmonic. Also, the "natural" frequency of the whole system (electron and photon) is that of the radiated photon. Consequences of these possibilities are not considered here.

[g] The acceleration $\mathbf{a}_x$ in eq. 2 is that of the charge at (t – r'/c) projected at right angles to r'.

[h] In the far field, the "retarded distance" r' is the distance from a non-relativistic source to the point of interest at t_2.

compact. The new waveform[i] decays (spatially) faster than 1/r (Figure A-1B) and therefore the radiation field is "contained," not radiated away.

In actuality, Feynman did not prove that single EM pulses from an accelerated charge radiated away. Therefore, his demonstration cannot be "simply" extended to the 'impossible' case of single pulses from decaying orbital electrons. On the other hand, neither can its failure be used to prove that single-pulse photons are not formed under these conditions. Therefore, quantum mechanics, which teaches that electron energy-level transition and photon creation is instantaneous (within the Heisenberg uncertainty principle constraints), is not directly violated. However, there are other problems.

Feynman, in his discussion of radiation damping,[e] extends the SHO model to explain the widths of spectral lines. An example he used gives the 1/e length of a representative photon as on the order of 10^7 oscillations. This clearly does not fall in the single-pulse regime. Nevertheless, it pushes the failure of validity of his argument to an interesting extreme. If the oscillator frequency is on the order of 10^{15} Hz, then during a radiative decay, the change in frequency is on the order of 10^{15} cycles/s in 10^8 oscillations – or about 10^7 Hz per oscillation. While this is a large change in terms of frequency, it is small in terms rate of change in cycle length. This change per cycle is only on the order of 1 part in 10^7. If this were the only consideration, then violation of the 1/r dependency is less than that and, to a high degree of accuracy, Feynman's "proof" could therefore be physically correct (even though it fails mathematically – and for other reasons). The shortening of the wavelength during the decay can relate to the uncertainty in momentum within a wave packet and could help to 'shape' a photon.

Unfortunately, the mathematical solution/interpretation for the radiation from an accelerating charge is only the beginning of the problem. The non-relativistic equations indicate that the radiation leaves in a dipole-radiation pattern. How does a single photon go off in a single direction from a decaying atom that radiates energy at the speed of light into 4π steradian solid angle? Does that not violate relativity? Furthermore, as seen from the text above, radiation from a non-circular electron orbit may have a waveform that differs greatly from that of a SHO. A ^{2}p (l = 1) to ^{1}s (l = 0) transition, becomes a periodic stream of intense EM spikes as the electron approaches the ground state with no angular momentum. (This pattern would be expected unless the electron delivers the required angular momentum in an abrupt "kick" near the end of the radiation-energy transfer). Can this spatially-divergent, grossly-non-sinusoidal, pulse train (spreading out in nearly all directions) become a photon (moving in one direction and not spreading at all)? Does, or could, application of classical electrodynamics to the photon model really fail? After all, Maxwell did not include photons in his equations.[j] Would it change things if he had? What if they were included now?

An additional question that must be addressed is the issue of radiation from the ground state of atoms. The classical equations state that a ground state electron should radiate. However, no radiation has been observed from this state (other than that proposed by Mills)[8] and the ground-state electrons do not decay into their nuclei. Unfortunately, quantum mechanics bypasses the issue rather than solving it. As an example, Feynman derives the equations for the hydrogen atom without including photons or radiation in the derivation (although he does use the proper 1/r potential in this case in his lectures). This is equivalent to denying the existence of a reaction channel and then stating that there is stability because there is now an energy minimum. A better approach is provided by stochastic electrodynamics (SED), which posits the existence of a random EM radiation field that is in equilibrium with and replaces the radiation energy lost from the ground states.[9] The source of this random EM radiation field has been described above.

Feynman's proof was not wrong, it just made the assumption (or at least leads the student to believe) that the radiation described was photonic. His radiation and the underlying assumptions are for externally 'driven' radiation, not from decay of excited atomic electrons. It is 'far-field', (to within parts per billion) and directional (e.g., dipole radiation patterns), just not in the manner that photons are. The assumption of simple harmonic motion is valid for small perturbations of a steady-state bound electron, even when in a Coulomb field. (The change in oscillator frequency from the perturbation is negligible – and periodic.) The proof fails for transitions of low-lying electrons

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[i] Since the electron moving in a Coulomb field is not necessarily SHO (e.g., if its orbit is not circular), its radiated waveform will not be sinusoidal (see text). Figures A-1 and A- 2 do use sinusoids. Nevertheless, Feynman's argument for the 1/r dependence of the SHO still fails for the non-SHO waveform and thereby the proof for no photonic radiation from a decaying atomic electron still holds.

[j] While Maxwell's equations do not predict photons, photons do not violate them. Photons just have something extra, which Maxwell did not need to include, since he didn't believe in them.

and unfortunately has misled generations of physicists. However, few physicists (and none of his engineering students) would ever get to a situation where this failure would be a concern.

Interestingly enough, Jackson,[10] in his derivation of the same effect, displays a similar oversight.[k] He does not include the important case that would apply to electrons in s orbitals that would transit nuclear regions. Thus, his derivation is fine for simple-harmonic oscillators, but (while possibly still correct) does not address some atomic-electron decays. (Unlike Feynman, he does not imply that he has covered that case. He does claim that there are 3 regions of interest and he does cover all those cases. The case that concerns us is not mentioned.)

This is part of the 'complication' of radiative decay, as distinct from radiation from a 'driven' charge. Nevertheless, if Feynman's demonstration for the radiation of a SHO waveform is valid, then our extension to prove the failure of decaying electrons to radiate photons (as complicated waveforms) should also be valid. If Feynman did prove that accelerating charges always radiate, but do not have to radiate photons, then we have to recognize that Einstein's photon model is valid and important, but not the whole story. Maxwell's equations are valid for radiation, even if that radiation is not in the form of photons. This leaves the discussion of non-photonic radiation open for consideration.

The wave-particle duality discussion (generally resolved by describing photons as being both particle and wave) may not have only a single answer. Electromagnetic radiation can be in the form of stable wave packets (photons), as meta-stable ensembles without distinguishable components (thus, they are wave fronts), or as EM pulses that decay with time and distance traveled. This third item is seldom studied or taught in physics classes and, while consistent with Maxwell's equations and talked about for more that 50 years,[11] has not yet achieved its proper role. Recognition of the physical reality of, and differences between, all three forms is important for understanding the fundamentals of physics.

The quantum mechanical description of non-radiation of ground states might be recognized as a "coincidence." Ground-state electrons just do not have enough angular momentum to decay photonically. The zero-zero transition is highly forbidden, even via a 2-photon transition. (However, if looked for and recognized as real, radiation from these transitions might be found, probably in the >25eV range.) The resonance conditions between electron and photon frequencies of the proper energies for sub-ground-state transitions are progressively weaker and this reduces the probability of energetic photonic transition even further (particularly in the case of 2-photon decays).

Why is there no radiation observed from electrons that are stable in non-ground state levels and not claimed to be at energy minima? The statement that they cannot radiate because "they would then decay to lower levels that are filled, and that would violate the Pauli Exclusion Principle," may be true; but, it is bad physics. It is almost the same circular argument used for "non-radiation" from a ground state. It is a statement that bothered me as a student and probably "turned-off" many other young physicists. A more-satisfying statement could be that "the near-field (virtual-photon) radiation, bound to the lower-level electrons, alters the shape of the potential well giving greater stability to higher orbits and thereby preventing decay to an occupied lower level." Does this address the ground-state issue? Yes, if you assume a non-photonic, or self-generated near-field, background-radiation level sufficient to block the decay channel by replacing the energy lost due to radiation from the accelerating electron. Unfortunately, that argument opens up a path for classical physics to compete with (or incorporate) quantum mechanics and such a possibility is 'unacceptable'.

Is the near-field-balance argument incorrect? That is still to be determined, but the source of replacement energy for the far-field radiation must still be addressed. Since all bound electrons radiate, there is a very high level of EM radiation throughout space (mostly non-photonic, since there are many more radiating electrons than electrons decaying to lower orbits via photonic radiation). If this non-photonic radiant energy were not "recycled," it would become nearly infinite (just as all bound electrons would spiral into their nuclei). It would appear that some form of equilibrium is a natural state. Now we are addressing zero-point energies, dark energy, and dark mass in the universe. (The concept also answers many other questions in physics.) A useful comparison is that of Brownian motion. Non-photonic energy can be transferred to charged particles (electrons, bound or free) in the statistical

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[k] Jackson says, "...we can make a Fourier analysis of the time dependence and handle each Fourier component separately." He identifies 3 regions of interest, but ignores the case(s), where the source region d is not "much smaller" than the radiation wavelength, λ, e.g., for a relativistic electron. Thus, within a page, he makes a simplifying assumption ($d << \lambda$) and an approximation that any waveform can be represented by a finite power series. This suggestion is violated by the extremely-high-frequency radiation components provided by s electrons near the nucleus.

fluctuation of the huge amount of this radiation. Since accelerated electrons reradiate this energy, equilibrium exists. This concept also might explain why un-stimulated emission can compete with stimulated decay in many cases.

If non-photonic radiation exists, why hasn't it been detected? Well, all of our radiation detectors are photon detectors (except for thermometers, etc.). How do we separate non-photonic from photonic radiation? We can't, if, as does QED, we define all radiation as photonic (e.g., near-field radiation consists of longitudinal "photons" as well as transverse photons)! Would we deny the existence (based on microscope observation) of Brownian motion in dust particles, if we could not detect its source, atoms and molecules? Probably not! But the explanation would differ. When quantum mechanics needed some help to explain things, "virtual photons," instantaneous creation/annihilation of electron-positron pairs out of vacuum, or "quantum foam," rather than classical (Maxwellian) non-photonic radiation, was the answer. Why is there still such aversion to the concept of non-photonic radiation?

Now that near-field scanning optical microscopy[12] (NSOM, using evanescent waves) is a maturing field with commercially-available products,[13] perhaps non-photonic radiation will become a legitimate field for study in modern physics, quantum mechanics, and quantum electrodynamics. It might even answer some of the disturbing questions about fundamental physics and cosmology.

Feynman made some assumptions (not all justified), to 'prove' to his students that, classically, all accelerated charges radiate. He followed his training and great intellect to teach what he thought was correct and how quantum mechanics was necessary and sufficient to replace classical physics. However, since Einstein showed that EM radiation was photonic (via the photoelectric effect)[1] and Maxwell had provided the "only" alternative (waves), no one sought beyond that controversy for other forms of radiant energy. Therefore, the possibility of non-photonic discrete radiation, as an alternative, was never an issue to be researched and taught. QED claims that evanescent waves are photonic (by definition) and does not need to examine the implications. Quantum mechanics 'solved' the problem of non-radiating ground states, and the issue went away.

This paper is to raise questions and is not intended to solve them all. It is hoped that the brief statement as to the existence and source of non-photonic radiation, which will not obey the black-body radiation limits imposed on photonic radiation, and can contribute to the revival of many fields of physics.

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[1] Feynman defines classical physics to be fixed at pre-1905 by its inability to explain this discovery (and that of relativity). Therefore, it is not allowed to incorporate anything beyond that time.