



Nature of EM waves as observed & reported by detectors for radio, visible and gamma frequencies

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ABSTRACT

Characteristic transformations measured by detectors indicate what conclusions we can draw about the signal we study. This paper will review the models behind the interaction processes experienced by detectors sensing radio, visible and gamma-ray signals and analyze why the conclusions about the nature of EM-waves should necessarily appear to be different and contradictory. The physical interaction processes between the EM-waves and the material in the different detectors - the LCR circuit, photo and gamma detectors - differ considerably. So drawing a definitive conclusion regarding the nature of EM-waves is fraught with pitfalls. We discuss how to bring conceptual continuity among these different interpretations of the interaction processes by imposing some logical congruence upon them.

Keywords: radio waves, light waves, x-rays, gamma-rays, nature of EM waves, detection of EM waves, detection, detectors

1. INTRODUCTION

We experience and learn about our universe by using various detectors - some of them "built in" (our eyes, sense of smell, hearing, touch etc.) and some external (CCDs, microphones etc.). First and foremost, one needs to remember that such detectors represent the *only* way we interact with and gather information about the physical world. Furthermore, we often seem to forget the fact that all detectors have inherent limitations with regard to the information they can convey to us. Different detectors have different limitations. Just as in the old Indian story about the blind men trying to visualize an elephant by using their sense of touch, we have to realize that one and the same thing can appear differently depending on how we "look" at it.

For a long time now we have known that radio waves, optical light and x/γ rays all represent a slightly different manifestation of the same physical phenomenon: electromagnetic (EM) waves. All of the mentioned waves have in common such properties as their characteristic speed of propagation (c), diffraction (observation of which we still lack for hard x-rays and γ rays), and we can do spectroscopy due to their oscillatory nature of fixed frequency.

Despite all this, the area seems to lack conceptual continuity, largely due to the perceived differences in the three types of radiation. In the following sections, the authors will review models of the different interaction processes that take place in detectors for the various types of EM-waves, and discuss how we can avoid many of the 'paradoxes' associated with EM-radiation by knowing and considering the specifics of the detection process.

2. DETECTION OF EM-WAVES

We approach the subject from the vantage point of the Non-Interference of Waves (NIW)-principle,¹ i.e. the fact that light does not interact with light*. Only material dipoles can 'see' light, and then only through their unique band-limited goggles. The information they can gather about light always lacks completeness. Humans have not succeeded in inventing any instrument that has 100% fidelity in transferring the information gathered by the detecting dipoles to final data recorders. This we call the 'Permanent Information Challenge' nature has imposed on us; by this we do not mean a simple Measurement Problem that we can solve by brilliant mathematical theorems.

*When referring to 'light' here and in what follows we will usually also mean all (EM) waves in general.

Given the cultural paradigms (models) that dominate different human neural networks for thinking, we will always plug in our personal biases to supplement the missing information using our own judgements (hypotheses) and override nature's insufficient information challenge. All of our mathematical theories, irrespective of their overriding historical successes, always represent incomplete theories, as we have created them based upon insufficient information about the system of cosmic logics.

2.1 Radio Frequency (RF) Waves

The detection of RF Waves physically corresponds to an energy transformation, typically occurring in LCR tank circuits, which we can analyze classically. The LCR circuit receives multiple radio signals from an antenna, a conductor in which semi-free electrons respond to the electric field of the impinging EM waves. Upon resonating, this produces an undulating AC signal made up of the conduction electrons in the circuit, which oscillates at the same frequency as the incident radio wave, as seen in Fig.1.a. If the incident radio wave consists of several distinct frequencies, and the circuit has the necessary broad response, then the AC signal consists of a linear superposition of alternating currents at the incident frequencies (Fig.1.b). This makes the signal amenable to analysis using Fourier mathematics.

Most importantly, in RF detection the LCR circuit generates "classical" currents which maintain the frequency information of the detected wave(s). One can only conjecture, what textbooks would say about photons if optical detectors behaved like radio wave detectors, and maintained the frequency information during the detection process.

As previously stated, a RF detector consists of an antenna connected to a tuned LCR circuit whose resonance we can set such as to select a specific frequency out of the many received by/at the detector. The conduction electrons within the circuit respond to an induced EMF at the radio wave frequency. These electrons then absorb energy from the EMF and oscillate within the LCR circuit, producing a measurable electrical current. This AC signal looks like the radio wave, with the exception of a relative phase shift w.r.t. the actual wave.

We can describe the EM-wave mathematically by $E = a \cos(2\pi\nu_0 t)$ and we can write the induced AC signal as $I = \eta a \cos(2\pi\nu_0 t + \phi)$, where η represents the energy transfer coefficient, and ϕ the phase shift. Again, note that we do not lose the frequency information during the detection process. Also note that, in general, η depends on the frequency, i.e. that $\eta = \eta(\nu)$.

Now, let us consider the behaviour of such a circuit with two waves with different frequencies ν_1 and ν_2 superposed, i.e. present at the same time in a volume occupied by the detecting antenna. Furthermore we assume a frequency band wide enough to accommodate both of these frequencies, that the amplitudes coincide and that η does not vary with frequency within the resonance band:

$$\begin{aligned} E_1 &= a \cos(2\pi\nu_1 t) \\ E_2 &= a \cos(2\pi\nu_2 t) \end{aligned}$$

In this case, the LCR circuit actually performs Fourier synthesis of the two signals, and what we register corresponds to

$$I = \eta E_1 + \eta E_2 = 2\eta a \cos\left(2\pi \frac{\nu_1 + \nu_2}{2} t\right) \cos\left(2\pi \frac{\nu_1 - \nu_2}{2} t\right) \quad (2.1)$$

i.e. we see a signal at the *mean* frequency $\Omega_1 = \frac{\nu_1 + \nu_2}{2}$ with an envelope frequency of $\Omega_2 = \frac{\nu_1 - \nu_2}{2}$ (see Fig.1.b).

2.2 Optical Waves

Unlike in the case of RF waves, detectors for optical frequencies can only measure the energy - a quantity proportional to the square of the electric field. This means that we have a less direct measurement (since we do not measure the field directly anymore), and we also retrieve less information about the primary quantity (the E-field) as we lose crucial frequency information in the square-law transformation.

One can divide optical detectors into two categories: photon detectors and thermal detectors.² We will only consider photon detectors here, since the output of thermal detectors shows no frequency dependence at all.

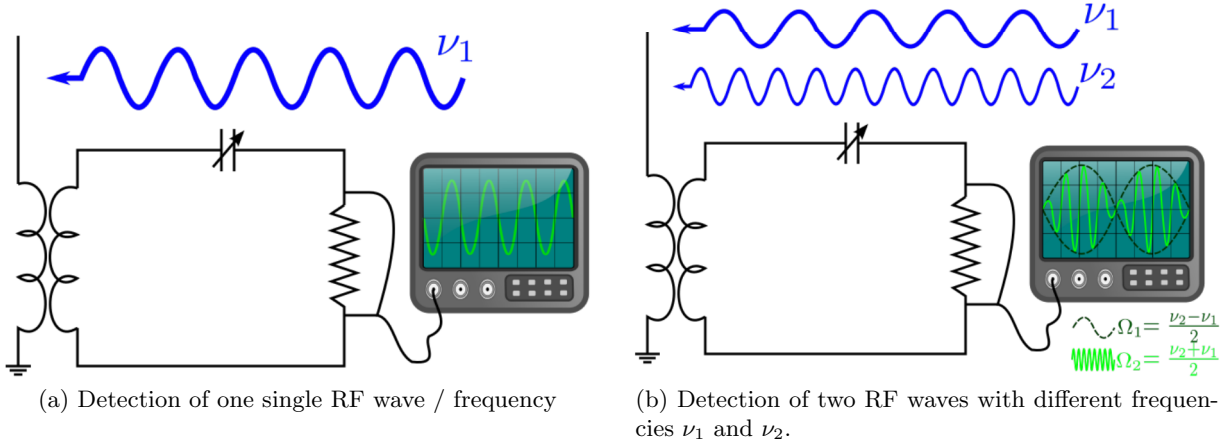


Figure 1: RF Detection using LRC circuit.

Once again, we could divide photon detectors into a number of different categories and look at each separately. All of them share their most important features and for simplicity's sake we shall instead consider a model that incorporates these features and which we assume to represent the fundamental physical process.

RF detectors directly measure the dipole-undulation induced by the impinging EM-wave. This represents a continuous process of energy absorption. Absorption and thus detection of visible light takes place in Quantum Mechanical (QM) detectors that exhibit discrete (quantized) energy levels or bands. As an example we can think of a simple atom, but the arguments will apply to any quantized QM device. In these devices, electrons can only occupy certain energy levels determined by the specific physical characteristics of the particular QM entity. In order for these electrons to change to a different energy state, they must either absorb or emit energy, depending on whether the change corresponds to increasing or lowering its energy. If the energy change comes about due to electromagnetic interaction, the emitted or absorbed quantity of energy follows the rule

$$\Delta E = h\nu \quad (2.2)$$

When considering wave packet emission, Eq.(2.2) tells us that the emitted packet will have frequency ν . On the other hand, in order to absorb EM energy the frequency of the impinging wave has to exactly match one of the frequencies determined by Eq.(2.2), which in turn depend on the particular quantum system. Detectors made from quantum systems such as atoms or molecules in a sufficiently dilute state, such as a gas, tend to exhibit sharp resonances (discrete energy levels), whereas solid state detectors tend to have energy bands, allowing for broad band detection.³

We can map and summarize the behaviour of these two types by using the linear (i.e. first order) susceptibility, or polarizability, of the atoms $\chi(\nu)$. Note that this quantity here depends on the (physical) frequency of the EM wave(s). For N different EM waves impinging on a detector, we can represent the absorbed energy (\mathcal{D}) mathematically as follows.*

$$\mathcal{D} = \int_0^T |d|^2 dt \quad (2.3)$$

Where $d \equiv \sum_{n=1}^N \chi(\nu_n) E_n$ represents the dipole-stimulation due to all of the EM waves. The restrictions of what does and does not get detected, based on the energy levels or bands actually present, lie encoded within $\chi(\nu)$,

*We will ignore the direction of polarization of the EM waves, as well as that of the material, entirely here, in order to keep the argument concise. Physically this means essentially that we have aligned everything such as to make the relative angle between EM polarization and polarization of the material vanish.

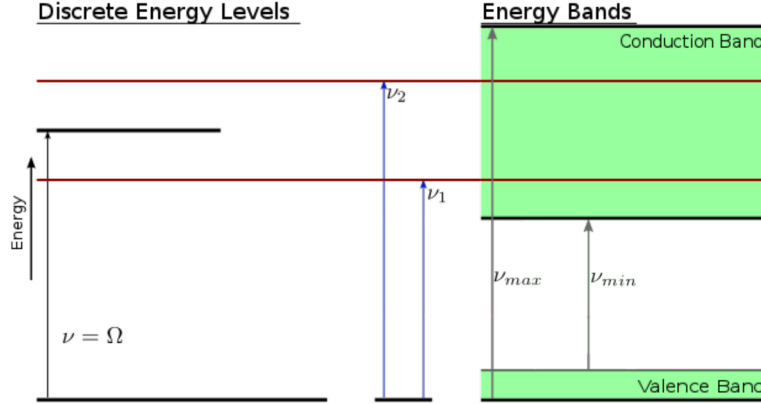


Figure 2: A detector with energy bands registers frequencies ν_1 and ν_2 , if they fall within the range $\Delta\nu = \nu_{max} - \nu_{min}$. Due to the NIW principle, a detector with discrete energy levels 'sees' nothing (as demonstrated experimentally⁵), even though the average frequency $\frac{\nu_1 + \nu_2}{2}$ corresponds exactly to the resonance frequency Ω of the system.

which equals zero if ν does not correspond to an allowed value. More concretely we can write this function as $\chi(\nu) \equiv \sum_i \kappa(\nu) \delta_{\nu, \nu_i}$ for the case of discrete levels, and $\chi(\nu) \equiv \sum_i \kappa(\nu) [\Theta(\nu - \nu_{min,i}) - \Theta(\nu - \nu_{max,i})]$ for energy bands (see Fig.2)*. Also note the time integration in Eq.(2.3). Each detector has a certain time constant, or 'reaction time', during which it determines its 'compatibility' with the frequency of a given wave packet and then absorbs energy accordingly. While this integration time may vary from detector to detector, when using complex notation and using the square-modulus we assume it equals exactly 2 periods of oscillation, as we show in another paper.⁴

These two types of detectors demonstrate how much the information we can get about a physical entity (in this case EM waves) can differ, depending on the detector we use. Let us, for example, consider two superposed plane waves with different frequencies ν_1 and ν_2 :

$$\begin{aligned} E_1 &= a \cos 2\pi\nu_1 t \\ E_2 &= a \cos 2\pi\nu_2 t \end{aligned} \quad (2.4)$$

Where we assumed equal amplitudes, for simplicity. Let us now consider a detector with a single energy level (beyond the ground state). If the resonant transition according to Eq.(2.2) corresponds to one of the two frequencies given in Eq.(2.4) the detector's output will report a value proportional to $\mathcal{D} = \frac{1}{2}\chi^2(\nu_1)a^2$ or $\mathcal{D} = \frac{1}{2}\chi^2(\nu_2)a^2$ respectively.

What happens if our detector has its resonance at $\nu = \Omega = \frac{\nu_1 + \nu_2}{2}$ instead? If we blindly assume that Fourier synthesis represents a principle inherent in the EM field, as opposed to a phenomenon whose validity depends on the properties of particular detectors, we would expect to see a response.³ However, the detector will 'see' nothing and thus report nothing back to us, because none of the original frequencies match its resonance frequency, and EM waves do not interact and thus cannot create the required frequency on their own.⁵

If, on the other hand, we have a detector with one *band* of allowed energies (see Fig.2), where ν_1 and ν_2 fall within the allowed band, the detector will respond to both frequencies simultaneously as indicated by Eq.(2.3): adding up the individual dipole stimulations, squaring and time-integrating. This detector uses an applied electric field to extract the conduction band electrons in form of a measurable current. This current, though, only exhibits the *difference* frequency ($\nu_2 - \nu_1$); the sum frequency ($\nu_2 + \nu_1$), as present in RF heterodyne[†], gets

* $\delta_{m,n}$ represents the (slightly generalized) Kronecker delta, $\Theta(x)$ the Heaviside step function, while $\kappa(\nu)$ determines the strength of the response. The subscript i here stands for one possible level or band transition. The sums run over all possible (read: allowed) transitions.

[†] which also follows a square-law

filtered out by the time-integration process. Mathematically, the result turn out proportional to:*

$$\mathcal{D} = \chi^2 a^2 + \chi^2 a^2 \cos 2\pi(\nu_1 - \nu_2)t \quad (2.5)$$

2.2.1 Direct optical E-Vector detection

Fairly recently Goulielmakis et al. developed a method of directly measuring the electric vector of a few-cycle optical pulse.⁶ By sending the pulse through a gas of Ne atoms, along side of an XUV pulse which can photoionize these atoms, the group measured the resulting kinetic energy which the optical pulse's electric field imparted on the now free electrons. Detection by such entirely free electrons likely represents the best method of detecting EM radiation (regardless of type) so far, as these electrons seem to have no frequency band limit (unlike the LCR circuit mentioned earlier), and thus should have the ability to perform Fourier Synthesis over an extremely wide range of frequencies.

2.3 x/γ Rays

X-rays and γ -rays represent the high-frequency end of the EM spectrum. We cannot clearly separate the two in terms of their placement in the spectrum as there exists some overlap. The distinction between the two stems rather from their origin, or generation mechanism. While EM pulses due to transitions of inner electrons get labeled 'x-ray', we call those originating from *nuclear* transitions γ -rays, even if some happen to have lower frequency than some of the x-rays. With this in mind, we should point out that this section will consider only such radiation that will require detection mechanisms markedly different from those described in previous sections. Detection mechanisms for lower frequencies correspond to those discussed when we looked at the optical regime. For this reason we shall refer to all the frequencies considered here from now on collectively as γ -rays, regardless of their origin.

Due to their high energy, and thus high frequency[†], the interaction of γ -rays with matter appears very classical. Furthermore, while visible light[‡] and other lower frequency radiation exhibits a significant amount of diffractive spreading, γ -rays do not seem to suffer from this effect, which generally behaves inversely proportional to the frequency in the far field, at all.

γ -radiation seems to mainly effect ionization of the matter it encounters. Thus, most, if not all, γ -ray detectors try to measure the results of such ionizations in one form or another. We will introduce the three main detector types here very briefly.² While the details of the actual detectors vary, they all have the key γ -ray interaction process (ionization), illustrated in Fig.3, in common.

2.3.1 Gas-Filled Detectors

Fig.3 shows a detector in which an inert gas provides the active medium with which the radiation will interact. A γ -ray will ionize a gas atom or molecule, thereby losing some of its energy, and move on to ionize another and another until it gets absorbed entirely. The voltage applied between the central wire and the outer cylinder accelerates the thus created positive and negative charges in opposite directions, creating an electrical current which subsequently gets measured.[§] This behaviour closely resembles that of an energetic *particle* entering the medium, knocking electrons out of their bound states and losing kinetic energy (i.e. slowing down) in the process. The γ -ray does not lose energy in terms of kinetic energy, however, since it has no mass and never stops moving at the speed of light c . Rather, its frequency diminishes according to Eq.(2.2).

*assuming $\chi(\nu_1) = \chi(\nu_2)$

†On the order of $10^{20} Hz$.

‡On the order of $10^{14} Hz$

§We ignore here the more intricate details of gas gain and saturation etc.

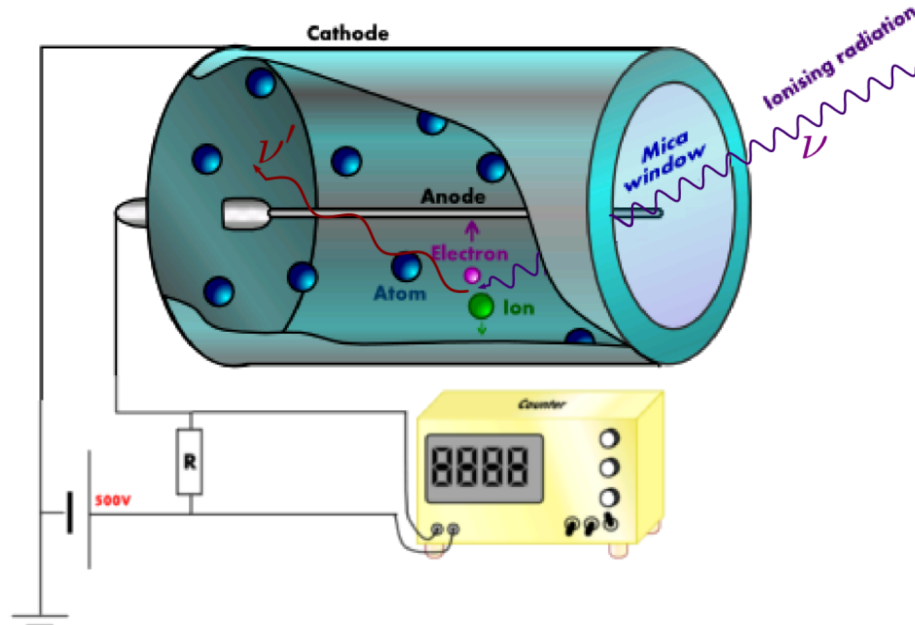


Figure 3: The γ -ray enters the proportional counter with frequency ν . After ionizing one of the atoms of the gas, thereby losing part of its energy, it continues to propagate, but with reduced frequency ν' . The voltage difference between the central wire and the housing of the device accelerates the charged particles in opposite directions as indicated, effectively producing a current which we can detect.

2.3.2 Scintillation Detectors

As we get to shorter wavelengths, the efficiency of gas-filled detectors declines and we require a different method of registering such radiation. Instead of a gas, scintillation detectors employ a large crystal* (the scintillator), typically thallium doped sodium iodide, as the active medium. Ionization within this medium does not produce free electrons as in the gas, but creates electron-hole pairs that end up recombining at impurity sites, which in turn causes the emission of typically visible scintillation light. This light then propagates through the crystal, transparent at these wavelengths, ends up getting amplified by photo multiplier tubes (PMTs) and converted to a measurable current. Again, one γ -ray will cause multiple of such interactions.

2.3.3 Solid-State Detectors

Much like in the case of optical radiation, the charge produced by ionizing radiation in solid state detectors gets collected directly, using an applied electric field, and converted into a measurable signal. Unlike detection of optical radiation in the corresponding detector, detection of γ -rays does *not* have its basis in a resonance process. As before, the highly energetic radiation directly imparts enough energy upon an electron to transfer it to the conduction band (creating electron-hole pairs), skipping the 'usual' determination of 'quantum compatibility'. The total energy of the incident γ -ray then gets determined using

$$E = n\epsilon \quad (2.6)$$

Where n represents the number of electrons detected (i.e. the number of ionization events), and ϵ corresponds to the energy gap between the valence band and the conduction band of the detector.

*or a volume of a suitable liquid

3. DISCUSSION

For over 100 years now, physicists have struggled with the so-called *wave-particle duality* of the photon*, as well as its inherent quantization as proposed by Albert Einstein†. We believe that there exists no justification for a particle model of the photon, nor for its inherent quantization. These concepts result from a number of physical effects and observations that seemingly got misinterpreted. In what follows we will consider a few of these, and give explanations consistent with the photon model we advocate.

3.1 The Photoelectric Effect

Let us first look at the photoelectric effect (PE), which we can summarize using the equation

$$K_{max} = h\nu - \phi \quad (3.1)$$

where the so-called "work function" $\phi \equiv h\nu_0$, ν_0 representing the minimum frequency necessary to liberate an electron from the given metal surface. ν represents the frequency of the incident radiation, and K_{max} the kinetic energy of the released electron.

Before release, the electrons within the metal surface exist in a bound state, not unlike those confined to a single atom. As in an atom, there should exist various different energy levels. Considering that we deal with metals when looking at the PE, it seems reasonable to assume that we have a continuum instead. Regardless, we should also have the ability to free the electron entirely - in the case of an atom, ionize it. Since individual energy levels‡ have a separation of $E_{m,n} = h\nu_{m,n}$ between them, and we can clearly find some energy at which we liberate an electron, it appears reasonable that the statement $E_{m,\infty} = h\nu_{m,\infty} \equiv h\nu_0$ holds true. We assume in the latter case, of course, that the level m refers to whatever corresponds to the energy level populated by the majority of the electrons in the metal surface. Any excess energy supplied gets converted to kinetic energy of the electron, $K_{max} = 1/2mv^2$. As in the electronic transitions in atoms, we lose the frequency information of the incident wave. None of this hints at, or requires photons (i.e. packets/pulses of EM radiation) to come only in amounts of $h\nu$, nor does this really tells us anything new about the properties of EM waves. It only gives information about how material media absorb energy from the field, namely that the available energy density of the incident EM field must exceed $h\nu$.

3.2 Transitions induced by particle collisions

We underscore the last statement by pointing out that elastic collisions between, for example, electrons and atoms can also effect transitions between energy levels, entirely without the presence of EM radiation. With enough kinetic energy, an electron can even ionize atoms this way. Let us look at a popular example: the He-Ne Laser. The first stage of the pumping mechanism consists of energetic electrons imparting part of their energy upon the He atoms, exciting them to either the 2^1S or the 2^3S state§. The electron thereby loses the energy needed for these transitions - $E_{1^1S,2^1S} = h\nu_{1^1S,2^1S}$ and $E_{1^1S,2^3S} = h\nu_{1^1S,2^3S}$ respectively - and consequently continues its movement at a lower velocity. We can characterize the kinetic energy of the electron after the collision by Eq.(3.2).

$$K_b \equiv \frac{1}{2}mv_b^2 = \frac{1}{2}mv_a^2 - h\nu_{m,n} \quad (3.2)$$

The subscripts a and b here refer to the electron *before* and *after* the collision respectively; m and n stand for one of the two transitions considered above. As written, Eq.(3.2) looks as though the atom absorbs a photon of energy $h\nu_{m,n}$. This demonstrates clearly that the quantized amount of energy 'belongs' to the atom, and *not* to 'the photon'.

*A concept which Louis de Broglie then extended to material particles.

†While many in addition assume indivisibility of photons, Einstein himself actually did not seem to want to exclude the possibility of, for example, partial absorption of photons by electrons.⁷

‡Because generalizing our statements from energy levels to bands seems straight forward enough, we will assume discrete levels here to make the argument conceptually more simple.

§These excited He atoms then transfer their energy to ground state Ne atoms by collisional exchange of this excitation, which then in turn become subject to stimulated emission.

3.3 Transitions induced by γ "particle collisions"

As seen in Section 2.3, it takes multiple ionization events to completely absorb the energy contained in a γ wave packet. Let us consider such a wave of frequency ν_0 . After the first interaction with an atom, its energy will have diminished by an amount E_i :

$$E_b = h\nu_0 - E_i = h(\nu_0 - \nu_i) \quad (3.3)$$

Where we defined $\nu_i \equiv \frac{E_i}{h}$. Evidently, as opposed to the collisions of the previous section, the γ -ray will continue on with a diminished frequency $\nu = \nu_0 - \nu_i$, and not diminished velocity (it obviously still propagates at the speed of light). Other than this, the interaction *appears* very much as that between particles. Due to the very high energy of the γ -ray, the interacting electron does not get the chance to 'check' for resonance conditions. The energy gets imparted directly and results in removal of the electron from the QM system (i.e. the atom). And once again, this demonstrates that we *cannot* think of photons as indivisible entities.

3.4 FELs

The Free-Electron Laser (FEL) provides further evidence that we can, at least in principle, create EM pulses of any frequency and length. More accurately, an *undulator** should have the aforementioned properties. Once we put it in a laser cavity to make a FEL, the pulse length becomes harder to set, but we end up with an (approximately CW) laser whose frequency does not depend on any atomic or molecular energy levels. Instead, we can set it very accurately by varying the electron energy. The electrons emit EM energy continuously in this case, and not in any quantized form. Mathematically, the frequency takes the following form⁹

$$\nu \approx \frac{2\gamma^2}{1 + \frac{1}{2}K^2}\nu_u \quad (3.4)$$

$$K \equiv \frac{eB_u\lambda_u}{2\pi m_e c} \quad (3.5)$$

Where we have: e =electron charge, m_e =electron mass, B_u =rms average undulator field, $\nu_u \equiv c/\lambda_u$, λ_u =length of one undulator period, c =speed of light in vacuum, $\gamma = v_e/c$, v_e =velocity of electron beam.

4. CONCLUSION

The fact that the energy level transitions always come in units of $h\nu$ does not say anything about the nature of EM radiation, as we have hopefully demonstrated. Instead, it represents an interesting property of matter and its associated bound states, which we need to try to explain. The assumption of a quantized EM field in free space by default prevents us from even recognizing that we need to investigate this particular fact.

Furthermore, we have shown that detectors only provide us with incomplete information about EM-waves[†], and the information that we do receive can only tell us about the *interaction process* between the actual EM-wave and the detecting entity. Trying to ignore the detector in the analysis of the results will lead us to conclusions contradictory to experimental observations, like 'indivisible photons'. We also have explained how γ -wave packets exhibit divisibility and deliver their energy in multiple steps.

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*Undulators consist of sets of alternating magnets and represent the essential component that makes FELs work.

[†]We can clearly generalize this statement to include *any* detector and measured quantity.

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