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Production of Photons in Positronium Decay: Critique of the Creation-Annihilation Hypothesis: Part I

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Abstract:

The history of the belief in the existence of elements from which all matter is formed begins more than two millennia ago with the writings of the ancient Greeks and Romans. Developments in the late 17th century pioneered by Robert Boyle led to the modern concept of elemental balance, according to which the number and type of various atoms remains exactly the same in the course of a chemical reaction. The concept of the creation and annihilation of matter changed all that. According to Einstein's relativity theory, elements can be converted entirely into energy and therefore no longer exist. The present study examines this theoretical interpretation by looking in detail at the process of positronium decay. It is suggested that the electron and positron constituents of positronium are actually bound so tightly together after decay that they form a massless lower-energy state which can be identified with the photon itself.

Keywords:

Photon, Positronium, Creation-Annihilation, Einstein $E=mc^2$, Mass-Energy Equivalence Relation

1. Introduction

After the discovery of quantum mechanics, nothing quite so excited the imagination of physicists as Dirac's prediction [1] of the existence of antimatter. Within a few years Anderson had demonstrated [2] the existence of the positron as the antiparticle of the electron, and within decades the antiproton [3] had also been found. Although Dirac's line of reasoning involved first and foremost his treatment [1] of the fine structure in the spectra of hydrogenic atoms, the ultimate theoretical basis for his prediction can be traced back years before to Einstein and the special theory of relativity (STR). [4] The famous mass-energy equivalence relation, $E=mc^2$, was given a more concrete interpretation by Dirac, namely that two particles of equal rest mass but opposite electric charge could be converted entirely into energy. In the case of e^+ and e^-, the energy appears as electromagnetic radiation or photons. The associated frequency ν is related to the energy E by the Planck relation [5] $E=h\nu$ (h is Planck's

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constant: $6.626x10^{-34}$ Js). A key element in this interpretation is the series of mechanical laws of classical physics, particularly the conservation of energy and each of the components of linear and angular momentum, which were enunciated in the seventeenth century by Newton [6] and Galileo. [7]

The creation and annihilation of matter, as this phenomenon is generally called, is central to the theory of modern physics, ranging from the sub-microscopic regime of atoms, electrons, photons and more exotic elementary particles to the super-macroscopic world comprising astronomy and cosmology. Indeed, one uses these terms to discuss processes which are commonplace in our everyday experience, such as the absorption and emission of light. Energy released or gained upon electronic transitions in atoms or molecules is said to cause the creation or destruction of a photon, again in accordance with the Planck energy-frequency relation.

As with other fundamental theoretical concepts of natural science, the principle of creation and annihilation of matter forced a rethinking of old themes from the realm of philosophy and metaphysics.

For example, a new interpretation could be given to the famous statement [8] of Lucretius in the first century B.C. in *de Rerum Natura: "*Nothing can be created from nothing," which is paraphrased by Shakespeare [9] in *King Lear* as "Nothing will come of nothing." In other words, energy in the form of photons corresponding to a given frequency is to be distinguished from nothing and therefore the production of electrons and positrons from it is thus not inconsistent with Lucretius's rule.

Yet, it is clear that the creation-annihilation concept still represents a revolutionary departure from ancient precepts, particularly certain aspects of the atomic theory of matter dating back to the work of Democritus. [10] According to this traditional view, the elements from which all matter is assumed to be constructed possess very definite characteristics. Again, in the words of Lucretius: [11] "Material objects are of two kinds, atoms and compounds of atoms. The atoms themselves cannot be swamped by any force, for they are preserved indefinitely by their absolute solidity." Suffice it to say that the annihilation of an electron and positron to produce pure energy is not consistent with this statement. The present investigation concerns itself with the theory underlying this revolutionary process in which material particles interact with one another with such force that they are claimed to lose the very identity that Lucretius imagined was their inherent property.

2. Positronium Decay and the Creation-Annihilation Hypothesis

In a book [12] published in 1661 entitled *The Skeptical Chymist,* Robert Boyle originated the modern concept of chemical elements. Simply stated, he suggested that the elements can be distinguished from all other substances by virtue of the fact that they cannot be split up by chemical reactions into simpler substances. The relationship between his ideas and the atomic theory of Democritus and continuing on to Lucretius is unmistakable. The concepts were made more concrete in Dalton's atomic theory [13] which was proposed in 1803. It provided a sound basis for interpreting known facts of chemistry. Thus, when one observed two different gases, oxygen and hydrogen, coming together to react explosively to form steam, one could speak of the process as involving two elements which were simply joined together in different ways before and after the reaction.

Until the advent of Einstein's STR [4] it was believed that each element had a fixed mass and that the sum of the masses of the reactants was exactly equal to that of the products. Even today one adheres to the underlying principle that the numbers of each type of element are unchanged in the course of chemical reactions, and thus the concept of a balanced equation remains an integral part of the teaching of fundamental chemistry to the present time. Special relativity merely rejects the assumption of fixed masses for the elements and replaces it with the principle that energy absorbed or emitted in the course of a physical transformation must be taken into account by means of the $E=mc^2$ relation in order to predict the combined mass of the products from that of the reactant species.

The concept of elemental balance in chemical reactions is in no way disturbed by this adjustment, and with its help it was possible to carry over the ideas of the early chemists to the interpretation of nuclear reactions involving much larger energy changes. For example, when two deuterium atoms combine to form an alpha particle the energy released is great enough to allow for direct measurement of the corresponding loss of mass of the product system relative to that of the reactants. The discovery of the neutron by Chadwick [14] in 1932 made it possible to specify more precisely what the elements are in this process. The deuteron is thus a compound consisting of a single proton and neutron, whereas the alpha particle is the 4He nucleus composed of pairs of each of these elements.

Nonetheless, one of the casualties of the creation-annihilation concept is the principle of elemental balance in all physical transformations. The above example involving a nuclear process is more the exception than the rule in the theory of modern physics, particularly as one makes the transition into the field of elementary particles. If particles can simply be converted into pure energy, there is no longer any basis for demanding that the same number and type of elemental species is present before and after a reaction has occurred. One need only try to imagine how the development of the theory of chemical transformations would have been affected *if the principle of a balanced reaction had not been enunciated* in order to appreciate the consequences of rejecting the idea in other branches of the natural sciences.

2.1. Electron-Positron Interaction

With this background it is interesting to analyze in some detail the process which first led to the postulation of the creation and annihilation of matter, namely the interaction of an electron with its antiparticle, the positron. For this purpose it is important to consider the experimental data with reference to familiar theoretical models without accepting their conclusions *a priori*, recalling Newton's prescription [15] that "these laws must be considered as resting on convictions drawn from observation and experiment, not on intuitive perception." Assuming the positron and the electron to be initially at rest, the first observation is that they form a weakly bound complex known as "positronium." After a short lifetime (ca. 10^{-10} s) something much more dramatic happens to the system, however. In the most commonly observed process, the decay of positronium leads to the production of two high-energy photons which fly away in opposite directions to one another. In another branch of this reaction which occurs much less frequently, three photons appear. In the primary decay process the two photons are always found to show opposite polarization, whether circular, plane or elliptical, and have equal energy /frequency.

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The existing theory for these various observations can be summarized as follows. First, a typical low-energy phenomenon occurs, corresponding to the binding of the electron and positron together. This process can be described accurately in close analogy to the treatment of the hydrogen atom by means of the non-relativistic Schrödinger equation. An even more thorough description in terms of quantum electrodynamics is also possible.[16] One knows that the ionization potential of the hydrogen atom is 13.605 eV (0.5 hartree) and the Bohr theory [17] of 1912 had shown that the amount of binding is proportional to the reduced mass $\mu = m_1m_2/(m_1 + m_2)$ of the proton-electron system. The equality of the rest masses of the electron and positron leads to the conclusion that μ for positronium is only about half that of the hydrogen atom. Hence, the binding energy in this case is one-half as large (6.80 eV). However, the *instability of the positronium complex stands in sharp contrast to the known characteristics of the corresponding H atom,* which is quite stable and appears to exist in this state for indefinite periods in the absence of any outside influence. [18]

Were it not for the spontaneous decay of positronium, one would have no difficulty relating these observations to Dalton's atomic theory. [13] In this case, the elements are one electron and one positron. At the beginning of the reaction they are separated (existing in elemental form, to use Boyle's terminology [12]), whereas afterwards the compound positronium is formed in which the two elements are bound together.

Why then must we give up the atomic theory of elements when it comes to the decay of positronium? The conventional answer to this question is that the elements with which we started, namely an electron and a positron, are no longer present at the conclusion of the process. Instead, one is left with a pair of photons in the most commonly occurring case.

Yet, in a strict sense the creation-annihilation explanation for positronium decay violates Newton's prescription about always basing theory firmly on observation. *How can one truly observe that something disappears?* If natural science is restricted to the domain of observation, how does one fit the phenomenon of creation and destruction into the picture? By definition, these processes involve material transformations either to or from nothing, and therefore can never be observed direct1y in their entirety. *There is clearly something about nothingness which defies observation.* By the same token, it is impossible to prove that things do not disappear. It only seems prudent to recognize that the inability to observe an object is not an unambiguous sign that it has ceased to exist.

Especially since the natural sciences underwent a long and successful development without having to yield on the ancient view that all material objects are synthesized from impermeable elements, it is important to probe the creation-annihilation hypothesis with utmost scrutiny. To this end, let us follow the tried-and-true principle of mathematics employed whenever a theorem is to be proven, *namely to assume the opposite and examine whether a contradiction can be derived as a result.* In the physical sciences the definitions of initial assumptions cannot always be as clearly drawn as in mathematics, however, so it is difficult to be certain that the list of alternative hypotheses has been exhausted. In the present discussion of particle-antiparticle interactions the finding of an incontrovertible hypothesis which does *not* require that matter is created or destroyed under any circumstances would have its merit, particularly from the point of view of the proponents of the classical atomic theory. To paraphrase another author with less direct involvement with the physical sciences who put these words in the mouth of Sherlock Holmes [19]: “When you have eliminated the impossible, whatever remains, *however improbable*, must be the truth.”

2.2. Is There a Non-Hydrogenic State Of Positronium?

In the first stage of the electron-positron interaction there is a close analogy to what is observed in the hydrogen atom formation. However, the fact that the 1s state of positronium undergoes spontaneous decay clearly distinguishes it from the proton-electron combination. In a broader sense, however, the positronium decay is similar to emission processes occurring in excited hydrogenic states such as the $^2P_{1/2}$ species, for example. After a short lifetime a decay photon is observed as the hydrogen atom returns to its ground state. Again quantum electrodynamics is able to describe this process with extremely high accuracy. The fact that no subsequent emission has ever been observed from the hydrogen $^2S_{1/2}$ state is why one refers to it as the ground state of this system. *But does this mean that the analogous 1s state of positronium is its ground state?*

The close similarity between the hydrogenic and postitronium spectra predicted by quantum mechanical theories ranging from the non-relativistic Schrödinger equation to quantum electrodynamics is the primary justification for answering this question in the affirmative, but the observed positronium decay from its 1s state raises at least the possibility that this conclusion is incorrect. *If there is a state of positronium below that of the 1s species, the observed photon appearance can be explained in a different manner.*

To explore this possibility let us examine the mechanics of the $P_{1/2}$–$S_{1/2}$ emission process in more detail for the hydrogen atom. The initial system is clearly the atom in one of its excited states, whereas the final system consists of the same atom in its ground state along with a photon associated with a characteristic frequency. With reference to what has been said previously, it can be noted that this theoretical description does not represent a balanced reaction in the traditional sense.

Nonetheless, there are clear similarities between this process and positronium decay from its 1s state. This can be seen by considering the distribution of energy and momentum among the partners of the transition. Because of the relatively large mass of the H atom, conservation of energy and linear momentum requires that the photon carry away most of the energy accompanying the transition, but not all of it. In order that momentum also is conserved in the process, it is necessary that the H atom recoil slightly relative to its initial position. The momentum of the atom is thus given by the de Broglie relation [20] as $p= h/\lambda$ (λ is the wavelength of the emitted radiation and h is Planck's constant). Consequently, some of the energy lost in the transition is also carried away by the H atom, specifically an amount equal to $p^2/2M_H$, where M_H is the total mass of the atom, i.e., electron plus proton. For higher-energy transitions, such as gamma decays in nuclear processes, the recoil energy can be so large that the energy of the emitted photon differs considerably from the internal energy difference of the pair of nuclear levels involved (Mössbauer effect [21]).

The decay of positronium can be viewed as similar in nature to the above emission processes, differing from them only in quantitative detail, provided one makes a crucial assumption, as outlined in what follows. It is generally accepted, for example, that the reason at least two photons are always observed after positronium decay is because of the need to conserve energy and momentum in the process. The rest masses of the particles present after positronium decay are equal, however, whereas in

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the other case the hydrogen atom is far more massive than the emitted photon. Consequently in the two-photon positronium decay the available energy and momenta are equally distributed whereas a much less equal distribution is found among the H-atom emission products. The assumption of a low-energy state of positronium below the 1s entity clearly would give more substance to this analogy, but there still remain difficulties as to how best to correlate the various product and reactant systems in the two processes.

To begin with, it seems straightforward to associate the emission quantum in the H-atom case to *one* of' the photons observed in positronium decay. The energies of the H atom and positronium photons are different to be sure, but so as to perfectly satisfy the pertinent conservation laws in each case. In order to make the analogy even closer, however, one might correlate the second photon observed in the positronium decay to the H-atom $1s_{1/2}$ product itself in the other example. The latter association is tantamount to saying that this photon continues to have the same e^+e^- structure as the initial complex, simply existing in a lower-energy state than the 1s species (see Figure 1). *Is something of this nature not a possibility?*

Pursuing this supposition further, it is important not to forget that both photons accompanying positronium decay (again in the most frequently occurring process) appear to be identical in every way, including with regard to their energies and absolute values of linear and angular momentum; only the directions of the latter two vector quantities are different, i.e., opposing. *There is thus no justification from experiment to attribute a different composition to one of the decay photons than to the other.* Before one can claim that particle balance has been achieved by the above assumption, however, it is necessary to face up to the fact that in this model there is apparently (at least) one more photon (even if its proposed e^+e^- structure is correct) present after the positronium decay than before it. At least there is comfort in realizing that the same state of affairs exists in the H-atom emission process, and therefore that the analogy under consideration is not weakened on this basis.

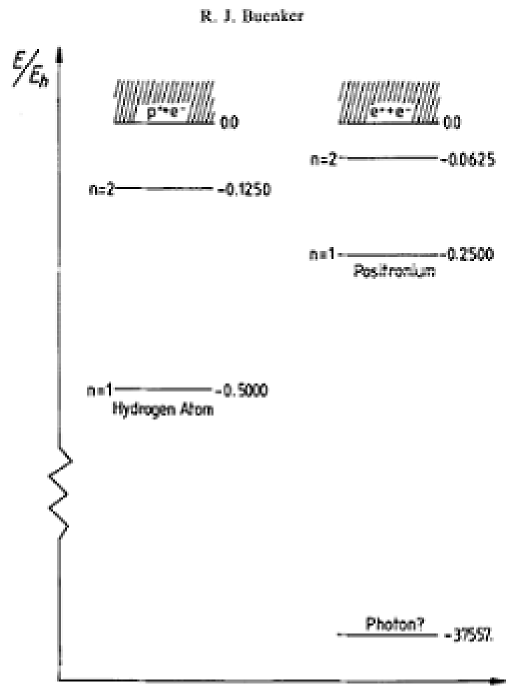

Figure 1. *Energy level diagram comparing the hydrogen atom and positronium.*

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In any atomic, molecular, nuclear or other radiative emission process, the conventional view holds that while the initial system consists of a single substance in an excited state, the final system consists of the same substance in a more stable state plus a photon of well-defined energy and momentum. Despite the universality of such processes, however, there is a way to describe them consistently, positronium decay included, without giving up the concept of complete particle balance. It is simply necessary to assume quite generally that the observed emission photons are also present *prior* to such transitions, *but that their energy and momentum are exactly zero in these initial states.*

In the standard quantum mechanical theory the lowest (1s) levels of each system occur at -0.5000 and -0.2500 hartree, respectively. Corresponding ionization energies for the excited states of these two systems always differ by a factor of two as well, reflecting the different reduced masses of the electron in the two cases. The hydrogenic ls state is known to be stable, however, whereas the corresponding e^+e^- state has a short lifetime and decays radiatively. This suggests that the true lowest state of the e^+e^- system actually lies far below the n = l state of positronium, and as such corresponds to the mass-less state of the photon itself, with an “ionization" energy equal to $2m_{oe}c^2$ or 37557.7306 hartree.

We come then to the crux of the creation-annihilation hypothesis. To deny the creation-annihilation proposition is to insist at the very least that photons with zero energy and momentum exist in their own right, despite the fact that according to the theory of special relativity they must be in a mass-less state under these conditions. Furthermore, the fact that radiative emission is observed whenever a system populates an excited internal state inevitably forces a new assumption, namely *that such mass-less particles can be found in sufficient numbers anywhere throughout the universe at all times.*

2.3. Relativistic Conclusions About Photons of Zero Energy

The concept of photons other than the real variety encountered in everyday experience is by no means foreign to physical theory. So-called virtual photons [22] play a key role in relativistic quantum electrodynamics and are invoked to explain details of the interaction of radiation with matter wherever it exists. Care is generally taken to exclude the possibility that such entities have any but a theoretical existence, however. One prefers instead to speak of them as a field quantity, with the non-localized properties of a wave-like substance, rather than simply as particles in the Newtonian sense. Even in classical electrodynamics it has long been known that there is a need to attribute non-zero energy and momentum to an electromagnetic field. [23] It is easy to find situations where failure to do this is tantamount to assuming that neither quantity is conserved in such processes. This line of approach is at least a clear indication that the *properties* of photons must be assumed to be present on a large scale everywhere in the universe, even if it is insisted that the particles as such are non-existent.

Why not actual particles, however? A typical argument is drawn from STR, asserting that once a particle with zero rest mass (as one assumes for a photon in free space) does not move with the speed of light c, it ceases to exist. The justification comes from the law of mass dilation [4]: $m= (1- v^2/c^2)^{-1/2}\ m_o = \gamma\ m_o$, where m_o is the rest mass and m is the relativistic mass of the particle moving relative to the observer with speed v. Accordingly, if $m_o= 0$ and $v < c$, then γ is finite and $m= 0$. On this basis

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it is generally concluded that the corresponding particle cannot exist.

Yet examination of this argument shows that the supposed non-existence of the zero-mass photon is really just an assumption. All one learns with certainty from the above formula is that $0 < v < c$ is a condition under which the relativistic mass of such a particle vanishes. *It does not say that the particle itself necessarily ceases to exist* as a result, however. The equation of non-zero mass with the possibility of a particle's existence cannot be said to be a logical consequence of the theory of special relativity. Instead, it constitutes an additional assumption which has had enormously broad consequences over the length and breadth of modern physical theory. At the very least it seems only prudent to give careful consideration to alternative interpretations of the possible meaning of a mass-less state of a system, as will be done below.

To begin with, it is possible to give a simple continuity argument which makes the existence of zero-mass photons plausible. Combining the mass-energy equivalence with the Planck frequency relation results in $E = h\nu = mc^2$. If $m = 0$, it follows that the corresponding frequency of the radiation is also of vanishing magnitude, whereas the wavelength $\lambda = \nu/c$ is infinitely large. A photon field with infinite wavelength is inaccessible to experimental detection and thus is not observable in the traditional sense. However, there is a clear distinction to be drawn between non-observation and non-existence. When an infinitesimal amount of energy is added to the same system, the above equation indicates that the photons now correspond to a non-zero frequency and a finite wavelength, which at least in principle can be measured. While there are definite limits as to how long a wavelength or how short a frequency can be measured in practice, it seems arbitrary to insist that beyond this point we dare not think of the particles as continuing to exist. If one can systematically withdraw energy from a single photon, at what point can it be safely assumed that it has been annihilated? The point is surely not that one can prove that a photon with exactly zero energy exists, but rather that *the converse cannot be proven* by this or any other means either. There is even a certain element of logic in dealing with the mass-less photon simply as *the limiting case in the above experiment* as the wavelength of the radiation becomes infinitely large.

Another mathematical point relating to the mass dilation formula should also be considered in the present context. If $m = 0$ for a particle of zero rest mass, must it continue to move at the speed of light? The answer based on the formula alone is clearly negative. Any value of the speed v up to and including c is consistent with zero relativistic mass for a system of zero rest mass. Even $v > c$ is not inconsistent, which fact, if nothing else, demonstrates that the mass dilation formula is really not at all restrictive on this point. The possibility exists in particular that a mass-less photon is *at rest* in a given rest frame, unlike photons with non-zero relativistic mass. There is no contradiction in this with regard to the postulates of STR, since such photons defy observation in any and all inertial systems. The photon in a mass-less state actually corresponds to the null world-vector of energy, which means that application of any Lorentz transformation with $v < c$ leaves it unchanged. This characteristic thus precludes the possibility that observers in inertial systems moving relative to one another would ever come to different conclusions about whether a given photon's mass is zero or not. A zero-energy photon thus remains undetectable to all observers regardless of their velocities relative to one another.

The same conclusion is reached by consideration of the relativistic Doppler effect, [24] which holds that the frequency of light as measured by an observer moving relative to the source with a speed v < c is a finite multiple of the frequency measured in the inertial system of the source itself. With reference to the thought experiment of the last paragraph, a photon with decreasing energy continues to move at the speed of light as long as its mass exceeds null. In the limit of zero energy, however, it becomes free to change its speed over a continuous range, although it must not do so. As a mass-less system, its momentum is unaffected by a change in velocity, so that a gradual reduction to zero velocity in any given inertial system is possible without altering its energy.

2.4. Statistical Mechanics of Massless Particles

In order to obtain a satisfactory explanation for spontaneous radiative emission which avoids the creation-annihilation hypothesis, it is not only necessary to assume that photons can exist with zero energy and momentum, but also that they exist in great numbers everywhere in the universe. One can approach this aspect of the problem on two levels. The first simply relies on the arguments of the last section and takes them a step further, namely if it is not possible to observe a single photon in this state, then it is also not possible to contradict the view that there are great numbers of such systems. However, it is also possible to find more positive indications regarding this point by considering the phenomenon of blackbody radiation.

Quantum mechanics originated with Planck's discovery [5] that the observed intensity distribution in a perfect absorber can be quantitatively described within the framework of Maxwell-Boltzmann statistics, provided one assumes that only certain energy values are available for radiation of a given frequency. Specifically, Einstein showed that the mean value of the energy is obtained as:

$$\langle E \rangle_{\nu} = \frac{\sum_{n=0} nh\nu \exp\left(\frac{-nh\nu}{kT}\right)}{\sum_{n=0} \exp\left(\frac{-nh\nu}{kT}\right)}$$

Rather than a ratio of integrals in which n is treated as a continuous variable with non-integer values. The key point of interest in the present context is that *the n = 0 term in the above sums must be retained* to provide for an accurate representation of the observed spectral intensity distribution. This term does not alter the sum in the numerator, but it makes a decisive contribution to that in the denominator (partition function).

According to the theory of statistical mechanics, each term in the above sums corresponds to an allowed state for the system, in this case a collection of oscillators or photons with energy $E_n = nh\nu$. The zero-energy (n=0) photon is thus an ingredient in Planck's long-accepted solution[5] to the blackbody problem. Moreover, as the lowest-energy state available to a photon associated with a given frequency, it is also the most frequently populated according to the Boltzmann exponential law, and this at any temperature T.

In order to obtain the total intensity distribution it is necessary to integrate over all frequencies from null upwards. It is important to note, however, that zero-energy photon states are present in the distribution for *each value of ν*. This situation is illustrated in Figure 2, in which the various frequencies are represented by the spokes of a wheel. The allowed states for a given *ν* can be thought of as being plotted as points along the corresponding spoke at a distance from the center of the wheel which is proportional to their energy. Especially if the Boltzmann populations are taken into account, it is found that by far the largest concentration of photons is at the center of the wheel, i.e. with exactly zero energy and momentum.

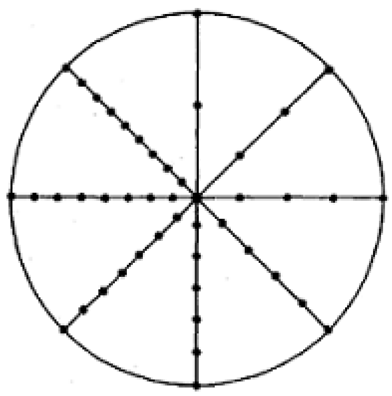

Figure 2. *Schematic diagram representing the distribution of allowed energy levels in the theory of blackbody radiation.*

Each spoke of the wheel corresponds to a fundamental frequency ν whose energy quantum E = hν is always proportional to the distance between adjacent points on such a radius. Each such (equally spaced) point thus corresponds to an allowed energy level, one of which is always found at the hub of the wheel for each spoke, i.e. E = 0 is allowed for every value of ν. The magnitude of the energy quantum is shown to decrease monotonically as one proceeds in a clockwise fashion from the twelve o'clock position. The partition function used in Einstein's explanation of the blackbody radiation phenomenon must include the E = 0 levels explicitly for each fundamental frequency in order to obtain results which agree with experiment. It is thus clear from the diagram that the highest concentration of allowed energy levels by far is located at the hub of the wheel, and the form of the Boltzmann exponential factors exp (-E/kT) insures that the highest photon population always occurs for this energy value.

Since a blackbody of a given temperature displays the same intensity distribution regardless of its location, it must be assumed that this state of affairs exists everywhere. The relatively high density of zero-energy photons is a theoretical assumption apparently needed to explain observed phenomena. This circumstance does not constitute a proof of the hypothesis in the mathematical sense, but at least it can be said that the idea does not lead to a contradiction either. Put the other way around, it would be a very damaging piece of evidence to the mass-less photon concept if states of zero energy had to be *excluded* from the partition function in order to achieve a satisfactory representation of the experimental observations. Quite to the contrary, Einstein made the opposite assumption of a high density of zero-energy photons. Seemingly the most natural interpretation for this theoretical approach is to conclude that the populations of *all* the various photon states are given correctly by the Boltzmann exponential factors in eq. (II.1), not only for those corresponding to non-zero quantum numbers. More details on this general subject may be found elsewhere. [25]

A different, and theoretically superior approach, was introduced by Bose [26], however. He concluded that Maxwell-Boltzmann statistics do not apply for photons.

Specifically, the population index for photons needs to be changed from exp (-E/kT) to (exp (E/kT)-1)$^{-1}$. This change has the effect of *greatly increasing the population of low-energy photons relative to the prediction of Maxwell-Boltzmann statistics.* In the present context, the key conclusion is that photons of *zero energy must be ascribed infinite population.* This result is thus the same as is reached using Einstein's quantization assumption discussed above, but the manner in which it is reached, namely on the basis of Bose-Einstein statistics, is completely in line with applications for atoms and molecules with non-zero rest mass.

2.5. Searching for a Quantum Mechanical Representation of The Zero-Energy State of The Photon

It is now of interest to shift the discussion from the general topic of radiative emission back to the original subject of positronium decay. By comparison with details of the hydrogen atom emission process, it was concluded that the appearance of only photons after positronium decay does not rule out the possibility that the internal structure of both the initial and final participants in this reaction is exactly the same. At least, the creation-annihilation hypothesis can be avoided by means of such an alternative assumption. In other words, it is proposed that the photon may also have an e^+e^- elemental composition, simply existing in a state of lower energy than the 1s species associated with positronium itself. The observed frequencies of the decay photons dictate that the energy of such an e^+e^- state must be $-2m_ec^2$ or -37557 hartree relative to that of the separated electron and positron, i.e. the negative of what one conventionally refers to as the annihilation energy. By comparison the energy of the positronium 1s state is -0.25 hartree (Figure 1).

Qualitatively one can imagine an attractive potential *which binds the electron and positron so tightly together* that there is a mass reduction similar to that known to occur in nuclear reactions. The difference in this case is that there is a total loss of mass, and not just a few parts in a thousand.

Moreover, such a tightly bound e^+e^- state can have no counterpart in the hydrogen atom spectrum. It is clear that quantum electrodynamics provides no such attractive potential or corresponding internal state, but one also knows that the range of validity for this theory is limited to electromagnetic interactions. Nonetheless, any conceivable extension of this theory to include a tight-binding e^+e^- state of the type required must remain consistent with the latter theory in its description of conventional electromagnetic phenomena. Before looking for a more quantitative model to describe such a positronium state, however, it is well to remain on the phenomenological level in considering the consequences that avoiding the creation-annihilation hypothesis have upon the interpretation of other experimental observations in modern physics.

3. A Survey of Other Experiments Involving Photons

The discussion in the preceding section demonstrates first and foremost that there is no compelling proof that particles pass to and from existence in the decay of positronium. It is impossible to distinguish between objects which have gone out of existence from those which simply cannot be detected experimentally. The alternative assumption to the creation and annihilation of matter is thus that particles can exist in great abundance in a mass-less (zero-energy) state without being directly observable. Put more descriptively, this amounts to saying: "*We live in an infinite sea of mass-less photons.*" The question to be explored in the present chapter is how these concepts can be used to explain other fundamental observations in modern physics.

3.1. Properties of The Photon

The interpretation of positronium decay as an emission process involving different states of the same physical system has been shown to suggest that the photon itself is a compound of a single electron and positron. It is therefore interesting to compare the properties expected for such an e^+e^- structure with those known experimentally for the photon. To begin with, it can be noted that a system containing two fermions in a highly bound state would be expected to obey the Bose-Einstein statistics observed for photons. The spin of the combined system must be integral, just as for positronium in any of its hydrogenic states. Whether a system consisting of an even number of fermions behaves as a boson or not is known to depend on the strength of the interactions holding the individual particles together. [27] The [3]He isotope, for example, is fermionic and non-superconducting, but combining it with another fermion (the neutron) produces ^{4}He, which behaves as a boson.

Otherwise, what we know of photons is that they have zero rest mass and no charge, the latter property being clearly consistent with an electron-positron composition. The fact that photons of a given energy are characterized by a definite frequency and wavelength does not distinguish them from other particles, as emphasized by the de Broglie relation [20] $p = h/\lambda$, and the Planck frequency law [5] $E = h\nu$, and demonstrated explicitly for electrons by Davisson and Germer. [28] For photons there is the additional feature of oscillating electric and magnetic fields being involved explicitly in the wave motion. However, especially for optical photons, the frequency of the oscillations is too large to enable a direct measurement of the individual electric or magnetic fields. [29] The oscillating properties of photons/light are actually deduced from theoretical considerations, namely the solution of Maxwell's classical equations of electromagnetism. [30] In quantum mechanics photons have traditionally been treated as oscillators, without giving a detailed description of the internal structure which is ultimately responsible for such characteristics. All that can be said in the present context is that an e^+e^- composition for the photon is at least consistent with electromagnetic phenomena.

The dipolar nature of such a binary system meshes qualitatively with the photon's capacity for interacting with charged particles, especially when the photon is in relative motion to the latter. One would have to have much more detailed information concerning the wave function of the e^+e^- system in a given state of translation to make more specific comparisons with real photons. Similarly, since the speed of the photons is a consequence of their zero rest mass, this is again a conceivable property for a system with such a dipolar composition, one whose verification would require a more quantitative theoretical treatment.

The polarization of light has been one of its most intriguing properties. It has been interpreted by Wigner [31] to result from the fact that the photon possesses non-zero angular momentum **J**. The "twoness" of the photon's polarization is thereby explained as a relativistic requirement according to which a particle moving with the speed of light must have **J** oriented either parallel or anti-parallel to its line of motion. Quantum mechanically this means that only $M_J = \pm 1$ is allowed for photons, despite the requirement of symmetry that components with $M_J = 0$ also must exist. Circularly polarized light corresponds to an eigen-function of J_z, while plane-polarized implies a 50-50 mixture of both allowed M_J values and elliptically polarized light is any combination in between, all of which is consistent with the existence of an effective two-fold degeneracy. Careful experiments [32,33] have demonstrated that the magnitude of a circularly polarized photon's spin component is $\hbar$, corresponding to $|J| = 1$, which is consistent with the Wigner interpretation, [31] but also with a possible e^+e^- constitution for the photon itself.

Altogether it should be recalled that despite intense investigation over centuries, going back at least to the work of Newton [34] and Huygens, [35] there is very little consensus about the structure of the photon itself, or indeed whether it has any internal structure at all. Einstein remarked [36] in 1951 that, despite his efforts of the preceding half-century, he did not feel that he had come any closer to answering the question of what a light quantum is. He went on to say that apparently many people [37] did think they understood the matter, but that they were only deceiving themselves. At the very least his comments would seem to allow considerable latitude for further research into this question.

3.2. Productlon of Particle-Antiparticle Pairs From Photon Collisions

The reverse process to positronium decay, in which an electron and positron are produced with the aid of high-energy photons, also needs to be considered in the present context. The assumption of an e^+e^- structure for each photon is obviously consistent with this result, but a few details require special attention. When a photon with energy equal to 2 $m_{oe}c^2$ collides with a massless photon, no electrons are produced unless a heavy nucleus is also present. By contrast, if two photons collide head-on, and each has $m_{oe}c^2$ energy, electron production is possible in free space. The distinction can be understood from relativity theory.

A collision between such a mass-less photon and one with $E = 2m_ec^2$ is characterized by a total momentum of $p = E/c = 2m_ec$. If one of the photons were to dissociate into its elements e^+ and e^-, all the available energy would be used up for this purpose, so that the translational energy of the two electrons produced would have to be null. The latter condition makes conservation of linear momentum in such a process impossible, however. By contrast, if both photons have $E = m_ec^2$ and collide head-on so that the momentum sum $\Sigma p_i = 0$, it follows that the electron and positron can be set free, but must remain at rest in the original inertial system. The latter process is seen to be simply the reverse of the positronium decay process, or more precisely the reverse of the interaction of a free electron and positron which are initially at rest in a given rest frame.

More generally, it needs to be recognized that for a given energy E, the momentum of the photon (E/c) is always greater than for any particle with rest mass $m_{0A} > 0$, for which $p_A=(E^2/c^2 - m_{0A}{}^2c^2)^{1/2}$. This fact prevents a single photon of any energy from causing a zero-energy photon to dissociate, because no matter how much energy is transferred, there is a disparity in the corresponding photon momentum lost and that which could be theoretically given to each of the electron products. The presence of a third body can remove this restriction, as is well known, but the point to emphasize in the present discussion is that the same result is found whether free space is thought to be involved, as foreseen in the creation-annihilation hypothesis, or if a mass-less *but existing* photon of e^+e^- structure is assumed instead.

To make this point more clearly, it is interesting to consider the effect of relative motion of the observer on the outcome of such experiments. The relativistic Doppler effect [23] tells us that the energy (frequency) of the photons in the above examples is dependent on the relative speed of the inertial system from which these quantities are measured. There is a clear exception to this rule, however, namely if the energy of the photon is zero in one inertial system, it must remain zero in any other. Thus, it is not possible to make the transition between the above two cases simply by changing the relative speed of the observer. As noted in Sect. II.C, a mass-less photon corresponds to a null vector in Minkowski space, [38] and as such is unaffected by any Lorentz transformation. At the same time, a photon with non-zero mass can have its energy changed to any conceivable value other than zero by virtue of such a transformation. The consequences of these relationships are crucial in the present case, with electron-positron production in "free space" occurring only if both photons have non-zero energy, just as is observed experimentally.

With much higher energies it is also possible to generate proton-antiproton pairs, [3] again as predicted by the Dirac theory. [1] It is clear that this result cannot be entirely explained by assuming an e^+e^- structure for the photon. Nonetheless, it cannot be said that such observations are inconsistent with what has been assumed so far. Rather, they force an additional assumption, namely that other types of mass-less particle-antiparticle binaries exist as well. There is, of course, a natural tendency to avoid introducing new types of particles into any theoretical framework, however. At the very least one hopes to keep their number to an absolute minimum.

As long as its rest mass is exactly zero, the mechanical properties already mentioned for e^+e^-, such as $\nu=0$, $\lambda = \infty$ and the like, could also apply to p^+p^- or related entities. One can only speculate that a p^+p^- system of zero rest mass will exhibit different properties under translation than do the corresponding e^+e^- species. Clearly, the dissociation energy of p^+p^- must be 1836 times greater than for e^+e^-, which condition already constitutes a major distinction. By the same token, the fact that neutron decay produces neutrinos, [39] whose rest mass is already close to or equal to zero, implies that there must be $\nu\,\bar{\nu}$ binaries as well, with extremely small to vanishing dissociation energies. The real challenge presented by these observations is to construct a quantitative theory, requiring as input at most such quantities as the rest mass, charge and perhaps magnetic moment of the interacting species, *which leads to binding energies of the above particle-antiparticle pairs which are equal to* $2c^2$ *times the rest mass of each of the respective constituents.*

Since the charge-to-mass ratio is much smaller for the proton than the electron, it seems clear that a p^+p^- binary would show much weaker electromagnetic effects than its e^+e^- counterpart. On this basis, it seems plausible that the traditional properties of a photon, i.e. oscillating electromagnetic field which is involved even in low-energy emission and absorption processes, are exhibited exclusively by the electron-positron mass-less binary systems. The statistical arguments given above, in conjunction with the discussion of blackbody radiation (Sect. II. D), are equally consistent with a high density of other systems of zero rest mass. At least one knows that protons and antiprotons can be produced together wherever the appropriate energy and momentum conditions are fulfilled.

3.3. Quantum Conditions of Photon Interactions

The quantum jumps associated with photon interactions provided an important clue regarding the particle nature of light. In his explanation of the photoelectric effect, [40] Einstein reversed a trend away from the Newtonian view [34] of light as "corpuscles." He showed that surface ionization of metals could be most consistently explained by

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assuming that a single quantum of light gives up all its energy to a single electron. He used the word "heuristic" in describing his ideas because the (exclusively) wave theory of electromagnetic radiation was widely accepted by the physics community at that time.

While there can be general agreement that the photoelectric effect is inconsistent with a totally wave-like nature for light, it still must be regarded as extraordinary that any particle would transmit *all* its translational energy to a single electron in a given interaction. Such a property of photons is consistent with the concept of annihilation, because it is reasonable to assume that a particle which has gone out of existence does so by leaving behind all its energy and momentum. However, if it is assumed instead that the photon retains its existence after photo-ionization has occurred, but simply assumes a mass-less state which defies direct experimental observation, it is necessary to look more closely at the dynamics of this process to better understand the nature of the quantization phenomenon.

To this end, it is instructive to apply the laws of energy and momentum conservation to the absorption process, as depicted in Figure 3. If the photon γ were to give off an arbitrary amount ΔE of its energy to an atom A with mass M_A, its momentum would decrease by $\Delta p_\gamma = \Delta E/c$. If the atom were to remain in the same internal state, this amount would appear in the form of translational energy, which means that the momentum of the atom would change by $\Delta p_A = (2M_A\Delta E)^{1/2}$. Conservation of momentum requires that Δp_A and Δp_γ be equal. For small ΔE this can never be the case, however, in view of the large mass of A. Setting Δp_A equal to Δp_γ shows that ΔE would have to be equal to twice the rest energy of A or $2M_Ac^2$, which corresponds to the GeV range [41].

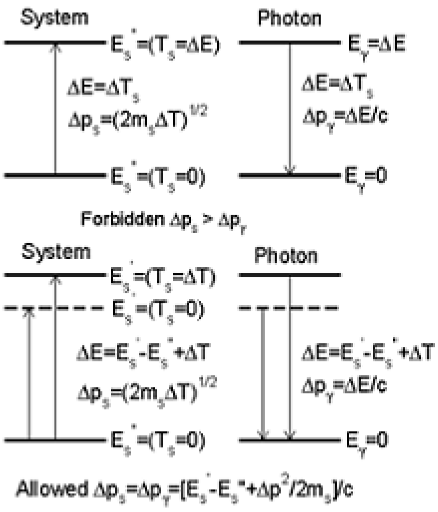

Figure 3. *Energy level diagram detailing the role of conservation laws in determining whether a given radiation absorption process is allowed or not.*

There is a solution to this dilemma, however, namely to have a part of the photon's energy be added to the internal energy of the atom, *i.e.* that another electronic state of the more massive system be reached. If the excited electronic state differs by hν in energy from that of the initial state, conservation of momentum requires that

$$\Delta p_\gamma = \Delta\frac{E}{c} = \Delta p_A = (2M_A)^{\frac{1}{2}}(\Delta E - h\nu)^{\frac{1}{2}}$$

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This is possible provided hν is only slightly smaller than ΔE, again by virtue of the relatively large mass of A as well as the magnitude of c.

It is important to distinguish between two aspects of the absorption process in the foregoing discussion. First, the quantized nature of the atomic spectrum is seen to be directly connected with the large disparity between the respective masses of the atom and the photon. When one considers the translational motion of the atom, it is recognized that the energy levels available to it are actually continuous. It is the requirement of momentum conservation which restricts the possible transitions between different states of the same atom and thereby produces the quantization phenomenon. On the other hand, on the basis of these arguments by themselves there is no restriction put on the magnitude ΔE of the energy lost by a photon in the absorption process, save that it be less than its total energy $E = m_\gamma c^2$. Indeed, the analogous excitation brought about by electron impact is well known. [42] One is thus still left with the conclusion that there is something special about a zero-energy, zero-momentum state of the photon, even though many aspects of the absorption phenomenon can be understood by just assuming that the photon is a particle of relatively small mass compared to the system with which it interacts.

At the top of the diagram, the system is to retain the same internal energy E_s" in the transition, *i.e.* the two levels shown differ only in translational energy $\Delta T_s = \Delta p_s^2/2m_s$ (non-relativistic theory), where m_s is the inertial mass of the system and Δp_s is the corresponding change in the momentum of its center of mass. Such a radiation process is always forbidden by the law of conservation of linear momentum because the rest mass of the photon is so much smaller than that of the system ($\Delta p_s > \Delta p_\gamma$). The only way for radiation absorption to occur is if the system changes its internal energy (from E_s" to E_s') as well as its translational energy, as depicted in the lower part of the diagram. Under these circumstances the momentum conservation law can be satisfied for a particular value of Δp_s, namely one that is equal to (E_s' - E_s" + $\Delta p_s^2/2m_s$)/c, where c is the speed of light. This condition rules out the occurrence of a radiation absorption process in which the system's translational energy does not change at all, also as indicated. Thus the "quantized" nature of radiation transitions is seen to be intimately connected with the photon's vanishing rest mass.

The fact that the energy transferred in the above process is exactly equal to $E_\gamma = m_\gamma c^2$ is thus seen to be a separate issue from the photo-ionization phenomenon itself. In other words, why doesn't the photon give off only part of its energy in inducing a transition in another system? Dirac used time-dependent perturbation theory [43] to answer this question, arguing that the incident radiation introduces a frequency-dependent term in the Hamiltonian of the atomic system. A resonance condition results according to which the energy of the most probable atomic transition, $h\nu = E_i - E_f$, must be the same as the energy of the incident photon, $E_\gamma = m_\gamma c^2$.

The prospect of a mass-less photon being formed as a result of this energy exchange (rather than that the original photon is annihilated in the process) suggests a somewhat different interpretation for this phenomenon, however, one which does not rely on the *ad hoc* assumption of wavelike properties for the incident radiation. If one simply looks upon the process as a collision between an atom and a photon moving with speed c, *it seems plausible to demand that the observed energy exchange take place over a relatively small but finite period of time.* As a consequence, the temporal requirements of the interaction are more readily fulfilled by an outgoing system whose velocity has been considerably reduced below the speed of light in a vacuum. As long as the departing photon possesses a non-zero amount of energy, this condition can never be fulfilled, but as has been pointed out in Sect. II.C, a *mass-less* photon is free of any such restriction, and thus can move at any speed less than c, including zero. In this view, the only practical means available to a photon to reduce its energy by virtue of an atomic collision is to assume a mass-less state, so that its relative speed compared to the system with which it interacts can be made as close to zero as possible. Accordingly, this interaction mode represents the only inelastic collision process available to a system of zero rest mass, since it is otherwise forced to move with the speed of light as long as it possesses any non-zero amount of translational energy.

By combining this result with the conservation of energy and momentum arguments first discussed, it is seen that the quantum characteristic associated with radiation absorption (and emission [44]) can be deduced exclusively on the basis of the rest mass values of the photon and the interacting system, respectively. There is no need to postulate any wave characteristics for the field inducing the transition. Instead, one is led to conclude from knowledge of the internal energy states of the interacting system and the magnitude of its rest mass exactly which photon energy is required to induce maximum transition probability. The magnitude of this transition probability itself cannot be determined quantitatively on the basis of the above information alone, and thus for this purpose one does have to introduce some additional information about the nature of the perturbing Hamiltonian, which itself is ultimately based on other experimental observations. This state of affairs does not affect the main conclusion in the present discussion, however, namely that the properties expected on the basis of relativity theory for a mass-less, but nonetheless existent, system are sufficient in themselves to allow for a suitable explanation of the observed tendency of photons to give up all their translational energy upon interacting with other particles.

These observations are also relevant to the positronium decay process discussed in Sect. II. In order for the de-excitation process to occur from the positronium 1s state to the proposed tightly-bound e^+e^- photon state (as depicted in Figure 1), it again seems highly desirable that there be a minimum of relative motion between its initial and final systems. This condition cannot be said to be satisfactorily fulfilled when the product photon carries translational energy, because it must then move away from the original point of interaction with the speed of light. That would be something akin to a business transaction carried out between two people, one of which is riding on a speeding train while the other is standing on the station platform. In its mass-less state, the photon can move with exactly the same velocity as the initial positronium system, thereby greatly improving the chances for such a transition. In this way, momentum can be conserved in the process, but the energy lost by the positronium complex still has to be carried away.

As shown in Figure 4, the simplest way to accomplish this objective is to have the released energy divided up equally between two other photons which are in the neighborhood of the interaction locale, which again means they must initially possess zero translational energy. The conservation laws can then be satisfied by dividing the emitted energy equally among the two departing photons and having them move with exactly opposed momentum. [25] There are also angular momentum conditions to be satisfied, which is why the number of emitted photons is different depending on the multiplicity of the positronium state prior to its decay.

By assuming that the photon also has an e^+e^- composition, it is possible to describe this transition without assuming that particles are either created or annihilated in the process. In this model three e^+e^- binaries are involved, two of which are mass-less photons at the start of the process. They share the energy released by the positronium decay, and are observed as γ photons of equal energy at its conclusion. The final state of the original positronium system is another mass-less photon which, exactly as its two counterparts at the start of the transition, escapes detection by virtue of its lack of energy.

To summarize, it is possible in this way to look upon the most commonly occurring positronium decay process (Figure 4) as involving three distinct photons, each of which exists in its mass-less state at some point in the interaction. [25] One of them is formed as a result of the de-excitation of the (singlet) positronium 1s state (Figure 1 and Figure 4), thus eluding detection by virtue of its null frequency. The other two are already present at the start of the reaction and are also unobservable as a consequence of their lack of inertial mass. Upon taking up their share of the energy released in the decay process they are detected, however, giving rise to the "two-photon" classification commonly ascribed to this interaction.

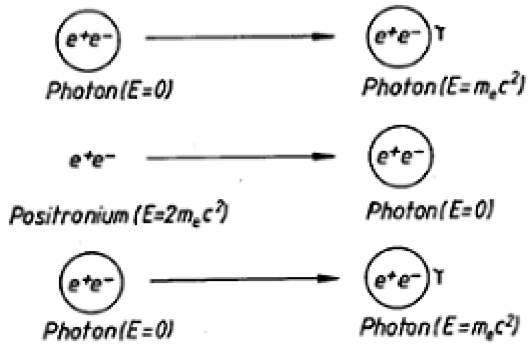

Figure 4. *Schematic diagram for the two-photon decay of (singlet) positronium.*

Another important aspect of this topic arises in the treatment of the blackbody radiation phenomenon. As discussed in Sect. II.D, Einstein's quantum assumption assigns allowed states to a given photon with only integral multiples of its frequency ν. Since a blackbody is a perfect absorber, each frequency is present, at least in principle, and one can think of such a system as a collection of atoms of the type just discussed. The success of Planck's assumption [5] indicates that each frequency can be treated independently of the other, however. It also is important to recall that equilibrium is present which is conventionally thought of as arising from a series of collisions between the participating systems over a long period of time. This suggests that photons of energy hν only interact readily with each other or with photons possessing a multiple of this energy. The same conclusion can be inferred from the occurrence of the coherence phenomenon [45] in electromagnetic radiation.

It seems at least possible that the stability of the photon in its mass-less state is at the root of the observed quantum characteristics of the blackbody intensity distribution. The special conditions of velocity seen to be permitted in this state, namely $0 \le v \le c$, are at least suggestive in this regard. The presumed high density of zero-energy photons based on the results of the blackbody experiment clearly derives from the fact that this energy value is the minimal amount available to photons in general. The key point which distinguishes the blackbody radiation phenomenon from the other processes discussed previously in this section is clearly that a large ensemble of photons is required to describe the effect in a meaningful way. It is not surprising as a result that it is quite difficult to analyze this particular experiment in the kind of microscopic detail needed to deal with the general question of whether individual mass-less photons can exist or not.

3.4. Compton and Raman Effects and Bremsstrahlung

The Compton effect [46] involves collisions between x-ray photons and weakly bound electrons and can also be interpreted in a very straightforward manner using conventional energy and momentum conservation arguments in conjunction with the Planck frequency and de Broglie relations. In this experiment a photon with a given energy is scattered off an (essentially free) electron and another photon is observed after the collision with lower energy and momentum than the first. It might be argued that the same (x-ray) photon is involved before and after the collision, but in view of experience with the absorption and emission of photons it is generally assumed that the first photon gives up all its energy initially and that afterwards this is distributed between the electron and a second photon. Again one conventionally speaks of annihilation of the first photon and creation of the second in the process, but one can just as well imagine that the first photon simply assumes a mass-less state upon collision, while another mass-less photon takes up the energy left over from the electron collision and appears as an x-ray photon, generally moving in a different direction than the first.

The Raman effect [47,48] is closely related to the Compton effect, and involves inelastic scattering of visible light off molecular systems. If the initial frequency is ν, it is found that photons emerge at right angles to the incident radiation with frequencies $\nu \pm \nu'$, where ν' is a characteristic infrared frequency which is small compared to ν. Again there might be a tendency to interpret incoming and outgoing photons as one and the same, only with changed energy, but the problems with this view are clearly the same in this regard as for the Compton effect. In both cases it is clear that a particle interpretation for the electromagnetic radiation allows for a quantitative description of these phenomena. There is no particular difficulty interpreting these effects in terms of mass-less photons located in the neighborhood of the pertinent collision processes.

Finally, it is pertinent in this connection to consider the Bremsstrahlung phenomenon as well. In this case an x-ray photon is produced with an energy which is essentially equal to the decrease in an electron's kinetic energy caused by its collision with a heavy nucleus. The process can thus also be thought of as an interaction in which a mass-less photon picks up energy, similarly as in the emission processes discussed earlier. The fact that a third (heavy) body is required is again related to the energy-momentum conservation laws, especially the fact that a given energy value always corresponds to a greater momentum for a photon than for a neighboring electron by virtue of the disparity in their respective rest masses.

4. Conclusions

In the present investigation attention has been centered primarily on the pervasive assumption in modern-day physical theories that matter can be created or destroyed by means of a suitable addition or loss of energy. It has been emphasized that it is impossible to distinguish experimentally between a particle which is unobservable in its present state and one which has gone out of existence entirely. The concept of all

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material particles being composed of atoms or elements which are impervious to the application of any force has played a crucial role in the development of the physical sciences over a period of several millennia. It has been argued in the present work that since the antithesis of this view, the creation-annihilation hypothesis, can never be proven by direct experimental observation, it is quite important to see if an alternative theory of physical transformations can be formulated which gives a plausible interpretation of all measured phenomena without giving up the principle of the indestructability of material elements.

Consideration of the decay of positronium and the subsequent production of photons, which has hitherto been assumed to involve the annihilation of an electron and positron, suggests a different explanation in terms of the formation of particle-antiparticle binary systems with exactly zero rest mass. In order to give quantitative substance to this alternative hypothesis, attention is turned to the goal of finding a suitably concrete form for the system of interactions which would be capable of binding an electron and positron so strongly together that the energy lost in the process is exactly equal to the sum of their rest masses, 2 m_{oe} c^2 or 37557.73 hartree (1.02 MeV). Instead of simply deducing this result with the help of the Einstein mass-energy equivalence relation, it is proposed to consider the positronium decay as a conventional radiative emission process in which the binding energy of the final state is to be computed with standard quantum mechanical methods once the nature of the associated interaction mechanism is identified.

In the course of studying other modern physics experiments on a qualitative basis, it has been concluded that such a massless e^+e^- structure can plausibly be attributed to the photon itself, since it is known to have zero rest mass and to interact electromagnetically in a way that is at least consistent with a dipolar composition of this kind. Because of the well-known fact that photon emission processes occur at all locations in the universe, i.e. wherever a given excited state of a particle is found to undergo radiative decay, it follows that the proposed massless e^+e^- binary systems must exist everywhere in space with sufficiently high density in order to explain these phenomena without the creation-annihilation hypothesis.

Support for this assumption of ubiquitous photons with zero mass can be found in the black-body radiation experiment (Sect. II.D). The original quantum hypothesis of Planck holds that for every frequency of radiation ν absorbed by a blackbody at thermal equilibrium, there must be a higher population of photons with E = 0 than for E = hν or any other allowed energy value. Since there are an unlimited number of such frequencies possible, it follows that the number of massless photons in the thermos-dynamical system is essentially boundless. It is then only a matter of theoretical interpretation whether occupation of such an E = 0 state is taken to correspond to a photon which has suddenly ceased to exist or *one which simply defies experimental detection.*

In this view the radiative emission process is not seen as involving the creation of a photon with ΔE = hν, but rather as an exchange of energy between the original excited system and a photon in its neighborhood which initially possesses zero energy. The photon simply takes on an amount of energy which is lost by the other system in a transition to one of its lower-lying states. Furthermore, the requirements of conservation of energy and linear momentum are shown to be directly responsible for the quantization of such processes, since an arbitrary exchange of energy would require a smaller increase in the photon's momentum than that lost by the heavier system with which it interacts. Only by changing to a lower-lying internal state with nearly the same momentum as prior to the transition can the heavier system satisfy the ΔE = pc relation required by the photon's zero rest mass. The explanation of the Mössbauer effect is based on the same considerations, with the distinguishing feature that for the very large energies of nuclear emission processes, the two internal states of the heavier system involved in the transition are associated with momenta which differ far more greatly from another than those of different electronic states in an atomic transition.

One of the most critical aspects of the massless photon hypothesis is its questioning of the off-stated belief that zero energy and/or mass for any system necessarily implies its lack of existence (Sect. II.C). Instead it is pointed out that the Planck frequency and de Broglie relations have zero frequency and infinite wavelength as limiting values when the energy and momentum of a photon approach vanishing magnitudes. Before this limit can be achieved by systematically reducing the energy of a single photon, frequency and wavelength values must be reached which by virtue of the above two relations already lie outside the range of experimental observation. Since photons whose (finite) de Broglie wavelengths are too large to measure are nevertheless assumed to exist, it is not unreasonable to expect that their zero-momentum counterparts may also be present, *despite the impossibility of observing them directly*.

In this connection a flaw is pointed out in the argument which holds that a system with zero rest mass must move with the speed of light based on the dependence of the relativistic mass m on velocity. The latter relation is satisfied for any velocity v smaller than c as long as m = 0, including v = 0. The ratio m_0/m is not uniquely defined under these circumstances and thus may exceed zero, *implying that* $\gamma^{-1} = (1 - v^2/c^2)^{1/2}$ *also can be non-vanishing in this limit.*

Consideration of other types of observed phenomena arising in the field of modern physics is found in no way to contradict the above hypothesis of ubiquitous massless photons. These processes include the photoelectric effect, Compton and Raman effects, Bremsstrahlung and electron production from photon collisions. At the same time, this line of argumentation calls into question standard interpretations of related elementary processes which involve the creation or annihilation of individual particles. The primary example considered in this connection is that of the beta decay of a neutron.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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