Pair production and annihilation as a nuclear process

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Abstract

The phenomenon of matter-antimatter pair creation and annihilation is usually taken as confirmation that, somehow, fields can condense into matter-particles or, conversely, that matter-particles can somehow turn into lightlike particles (photons and/or neutrinos) – which are nothing but *traveling* fields (electromagnetic or, in the case of the neutrino, some *strong* field, perhaps). However, pair creation always requires the presence of a nucleus. We, therefore, wonder whether pair creation and annihilation cannot be analyzed as part of some nuclear process.

We argue the usual nuclear reactions involving protons and neutrons can effectively account for the processes of pair creation and annihilation. We therefore argue that the need to invoke some quantum field theory (QFT) to explain these high-energy processes would need to be justified much better than it currently is.

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Introduction

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Carl Anderson's original discovery of the positron involved cosmic rays hitting atmospheric molecules, a process which involves the creation of unstable particles including *pions*.[2] Cosmic rays themselves are, unlike what the name suggests, *no* rays – not like electromagnetic gamma rays, at least – but highly energetic protons and atomic nuclei. Hence, *they consist of matter-particles, not of photons*. The creation of electron-positron pairs from cosmic rays involves these pions as intermediate particles:

1. The π^+ and π^- particles have *net* positive and negative charge of 1 e^+ and 1 e^- respectively. According to mainstream theory, this is because they combine a *u* and *d* quark but – abandoning the quark hypothesis[3] – we may want to think their charge could be explained, perhaps, by the

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[1] The usual reason that is quoted here has to do with excess energy and momentum that, somehow, needs to be absorbed. The Wikipedia article on pair creation, which quotes or summarizes from J.H. Hubbell's 2006 overview article on electron-positron pair production by photons, says this: "*The photon must be near a nucleus in order to satisfy conservation of momentum, as an electron–positron pair produced in free space cannot both satisfy conservation of energy and momentum.*" We think this explanation does not quite cut it.

[2] The discovery of the positron is, without any doubt, to be credited to the tireless efforts of Carl Anderson in the early 1930s. In contrast, the discovery of the pion – both experimentally as well as theoretically – is a more complicated matter. Nobel Prizes in Physics were awarded to Yukawa in 1949 for his theoretical prediction of the existence of mesons, and to Cecil Powell in 1950 for developing and applying the technique of particle detection using photographic emulsions, which were effectively used to confirm the existence of what was then referred to as *charged* π-mesons in an international effort led by Cecil Powell. However, some credit a young Indian scientist at the Bose Institute in Calcutta (now Kolkata), Bibha Chowdhury, with the actual discovery. She effectively discovered traces of the heavy ionized particles using photographic plates and apparently published on these discoveries in not less than three articles for the *Nature* journal in 1941 and 1942. As for its theoretical foundations, we think Yukawa's concept of a strong force makes sense, but we never quite understood the idea of it having to be *mediated* by a 100 MeV *virtual quantum*. See our paper on the nature of Yukawa's force and charge.

[3] You may be so familiar with quarks that you do not want to question this hypothesis anymore. If so, let me ask you: where do the quarks go when a charged pion disintegrates into a muon-electron (or positron), or into highly energetic photons? We think the invention of the concept of strangeness by Murray Gell-Man and Kazuhiko Nishijima in the 1950s may or may not have been useful as a *mathematical* concept. However, we feel this concept started a rather strange life of its own as it would effectively serve – much later – as the basis for the quark

presence of a positron (or an electron in the case of a π^-)! They effectively disintegrate into a muon-electron ($\mu^\pm$) which, in turn, will emit a neutrino[4] and morph into an electron or its positively charged antimatter counterpart ($e^\pm$).

2. The neutral pion is a very different animal: it (usually) disintegrates into two photons[5] which, in turn, somehow both *morph* into an electron and a positron – so we get two electrons and two positrons, and so that is the process which we want to think about in this paper.

The illustration below shows the (1) ingredients (the highly energetic proton and an atmospheric molecule) and (2) final products (one muon-electron/positron pair, two electron/positron pairs[6], and a neutron) of this remarkable process.

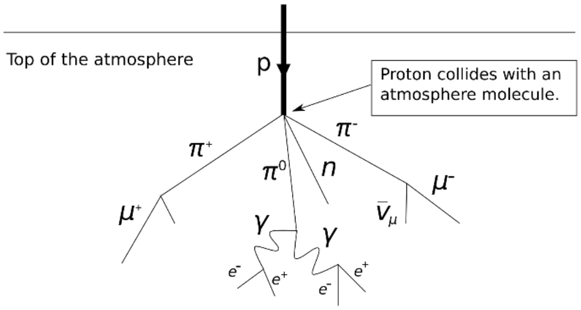

Figure 1: Pion production from cosmic rays (source: Wikipedia)

Before we get into the nitty-gritty of it all, we should make some few preliminary remarks:

1. Note that the illustration above might suggest that the whole process – from start to end – does not respect the charge conservation principle: the charge of the incoming proton is e^+, while the charges of the intermediate products (π^+, π^-, π^- and a neutron) add up to zero. However, while the lifetime of a (free) neutron is close to eternity (about 15 minutes), we argue one should think of it as combining a proton and an electron.[7] Hence, the proton balance before and after is OK, but we are missing an

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hypothesis which – for a reason we find even stranger than the concept of strangeness itself – was officially elevated to the status of a scientific dogma by the Nobel Prize Committee for Physics.

[4] To be precise, the process involves the emission of *two* neutrinos: a neutrino and its so-called antimatter counterpart. We think of neutrinos as lightlike particles, so there is no opposite charge here: we think the two neutrinos differ only in their spin.

[5] There are other decay modes, of course, but this is the principal one, and so we will look at this mainly.

[6] Because the $\mu^\pm$ will disintegrate into an $e^\pm$ (the lifetime of a muon-electron is 2.2×10^{-6} s), you may think of the final products as three electron-positron pairs (and some neutrinos, of course) and – lest we forget – the neutron. Note that a lifetime of 2.2×10^{-6} s is considered to be (almost) an eternity in particle physics. The Wikipedia entry on the microsecond has an animated gif which gives you an idea of what such time interval actually means.

[7] We know this sounds outrageous but we think it is justified because of the neutron decay reaction. A neutron does not decay into quarks or some other exotic thing. It decays into a proton and an electron: $n^0 \rightarrow p^+ + e^- + \nu^0$. Simple. We do not understand why some academics find it so difficult to accept what is written here or, worse, simply refuse to consider it as an alternative for the quark hypothesis.

electron. It should be added somewhere.[8] Where, *exactly*? We do not know, *yet*. It must be something with the atmospheric molecule.[9]

2. It is plain weird – or *artificial*, we should say, perhaps – that neutral pions are, somehow, being thought of as being similar to (charged) $\pi^{\pm}$ particles. The casual lumping together of $\pi^{\pm}$ particles and neutral pions under one and the same banner (pions) is like saying protons and neutrons are nucleons, both. That is an obvious truth, of course, but we do not learn much by it: we need to get into the nitty-gritty of neutron decay and other nuclear processes to understand how *different* they actually are, right? And the difference between neutral and charged pions is even starker.

For starters, neutral pions have a much shorter lifetime – in the order of 10^{-18} s only – than π^{+} and π^{-} particles, whose lifetime is a much more respectable 2.6×10^{-8} s. Something you can effectively *measure*, in other words.[10] And then, charged pions carry charge. Neutral pions do not. Huge difference! In short, despite similar energies, neutral pions do *not* seem to have a lot in common with π^{+} and π^{-} particles. Historically, charged pions were discovered in the late 1930s (and further confirmed in the 1940s), while the neutral pion was discovered in very different experiments in the 1950s only. We, therefore, wonder why neutral pions and π^{+} and π^{-} particles are to be thought of as, somehow, being similar particles.[11]

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[8] All kinds of weird things may happen to the *number* of charged particles – especially if they are only *intermediate* particles – but the matter-antimatter pair creation of annihilation does respect the overarching charge conservation law. Charge, momentum (linear and angular), and energy are always conserved, *somehow*. The invention of a zillion weird quantum numbers does not fundamentally challenge this.

[9] There are many possibilities here. The most obvious is an ionization of the atmospheric molecule: there is a very good reason why the upper layer of the atmosphere is referred to as the ionosphere, indeed! However, such ionization may not be the *direct* result of an electron being ripped out of a shell. The highly energetic proton might, perhaps, knock out one of the neutrons in the nucleus! It could then *morph* into a neutron by capturing an electron: $p^{+} + e^{-} \rightarrow n^{0} + \nu^{0}$. Is this what happens? We do not know. The point is this: in high-energy physics, we should forget about particles being conserved – obviously – but we should not forget *total charge must be conserved, somehow*.

[10] The point estimate of the lifetime of a neutral pion of the Particle Data Group (PDG) is about 8.5×10^{-17} s. Such short lifetimes cannot be measured in a classical sense: such particles are usually referred to as *resonances* (rather than particles) and the lifetime is calculated from a so-called *resonance width*. We may discuss (and criticize) this approach in a future version of this paper. Just note that, even at the speed of light, these particles would only travel $(8.5\times10^{-17}\text{ s})\cdot(3\times10^{8}\text{ m/s}) = 25.5\times10^{8}\text{ m}^{-9}$. That length is about 500 times the radius of a hydrogen atom, and a particle with a rest mass of 135 MeV can surely not aspire to travel anything near lightlike. So, yes, thinking of it as some kind of local unstable resonance – something which happens *at the scale of an atom itself* – is quite appropriate.

[11] Quark theorists say they have this in common: they all consist of a quark and an antiquark. We wonder what they mean by that – not approximately, but *exactly*? What explains the *very* different lifetimes and the *very* different decay modes? Aitchison and Hey answer this question in two volumes (*Gauge Theories in Particle Physics*, 2013) but, frankly, we find such long answer rather complicated and, therefore, unconvincing. The short explanation is that the neutral pion decays via the electromagnetic force, while the charged pions decay because of the weak force. We read this as follows: the neutral pion consists of opposite (electric) charges (which do not necessarily need to be quarks for us) while the charged pions (also) involve something else, which is not necessarily some weak force (we think of a force as holding something together, rather than as something pulling something apart) but, perhaps, some strong force. Such strong force must have a different *geometry* than the electromagnetic force or – who knows? – might act on a different charge, or both perhaps. However, we do not necessarily think of the concept of color charge here.

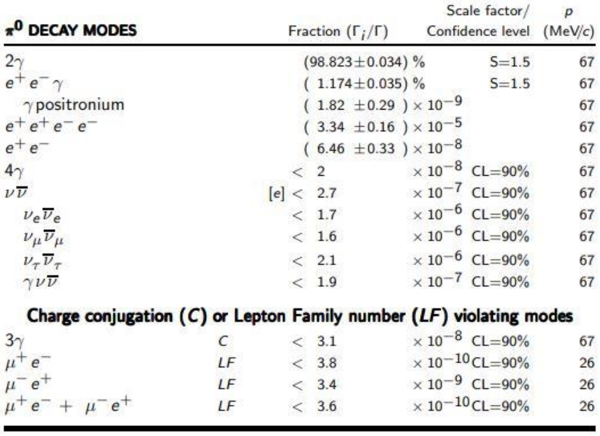
Even the energy difference is quite substantial (when measured in terms of the electron mass, that is): the neutral pion has an energy of about 135 MeV, while π^+ and π^- particles have an energy of almost 140 MeV. To be precise, the difference is about 4.6 MeV. That is quite a lot: the electron rest energy is 0.511 MeV only.[12] So it is *not* stupid to think that π^+ and π^- particles might carry an extra positron or electron, *somehow*. In our not-so-humble view, this is as legitimate as thinking – like Rutherford did – that a neutron should, *somehow*, combine a proton and an electron.[13]

The whole analysis – both in the QED as well as in the QCD sector of quantum physics – would radically alter when thinking of neutral particles – such as neutrons and π^0 particles – not as consisting of quarks but of protons/antiprotons and/or electrons/positrons cancelling each other's charges out. We have not seen much – if anything – which convinces us such thinking cannot possibly be correct. We, therefore, believe a more realist interpretation of quantum physics should be possible for high-energy phenomena as well. With a more realist theory, we mean one that does *not* involve quantum field and/or renormalization theory. Such new theory would not be contradictory to the principle that, in Nature, the *number* of (charged or neutral) *particles* is no longer conserved, but that total (net) charge *is* actually being conserved, *always*. Hence, charged particles could appear and disappear, but they would be part of neutral particles. All particles in such processes are very short-lived anyway, so what *is* a particle here? We should probably think of as an unstable combination of various bits and bobs, isn't it? 😊

However, we readily admit this was probably the longest introduction to a paper – *ever* – and that, nevertheless, some of the reasoning above may be considered to be rather sloppy and general. Let us, therefore, be much more precise.

Pair production as a nuclear process

The overview below (Figure 2) lists of all of the decay modes of a proton.



π^0 DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
2γ		(98.823 ± 0.034) %	S=1.5	67
$e^+e^-\gamma$		(1.174 ± 0.035) %	S=1.5	67
γ positronium		$(1.82\pm0.29)\times10^{-9}$		67
$e^+e^+e^-e^-$		$(3.34\pm0.16)\times10^{-5}$		67
e^+e^-		$(6.46\pm0.33)\times10^{-8}$		67
4γ		$< 2\times10^{-8}$	CL=90%	67
$\nu\overline{\nu}$	[e]	$< 2.7\times10^{-7}$	CL=90%	67
$\nu_e\overline{\nu}_e$		$< 1.7\times10^{-6}$	CL=90%	67
$\nu_\mu\overline{\nu}_\mu$		$< 1.6\times10^{-6}$	CL=90%	67
$\nu_\tau\overline{\nu}_\tau$		$< 2.1\times10^{-6}$	CL=90%	67
$\gamma\nu\overline{\nu}$		$< 1.9\times10^{-7}$	CL=90%	67
Charge conjugation (*C*) or Lepton Family number (*LF*) violating modes				
3γ	*C*	$< 3.1\times10^{-8}$	CL=90%	67
μ^+e^-	*LF*	$< 3.8\times10^{-10}$	CL=90%	26
μ^-e^+	*LF*	$< 3.4\times10^{-9}$	CL=90%	26
$\mu^+e^- + \mu^-e^+$	*LF*	$< 3.6\times10^{-10}$	CL=90%	26

Figure 2: The decay modes of the π^0 resonance

The table shows what we know already: a neutral pion (π^0) usually – this means 98.8% of the time here – decays into two photons. Occasionally (almost 1.2% of the time), it decays into a photon and an electron-positron pair but, according to Wikipedia, this is actually also a two-photon decay with one of

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[12] Of course, it is much smaller when compared to the proton (rest) energy, which it is about 938 MeV.

[13] See our short history of quantum-mechanical ideas or our paper on protons and neutrons.

the photons decaying into an electron-positron pair. Once in a million (see the 10^{-6} fractions), or once in a billion (see the 10^{-9} fractions), it decays into something else. We may or may not come back to those other modes in a later version of this paper. Let us first think about the main decay mode: two highly energetic photons. How energetic, *exactly*? And what happens with these photons, then?

Gamma rays from radioactive decay (*nuclear* gamma rays) carry energies up to 8 MeV, but so here we must be talking 67 MeV photons (half of the 134 MeV energy of the pion).[14] That is *huge*. When interacting with the electromagnetic fields inside of an atom and, presumably, within a *nucleus* itself, such photon must rip all apart – and it does! This is probably why the naturally occurring process of pion decay in the upper layers of our atmosphere usually shows the two photons creating electron-positron pairs *when interacting with other nearby matter-particles* (as shown in Figure 1, indeed). So how does that happen – not approximately but *exactly?* We must, of course, think of the four principal nuclear processes here:

1. Neutron decay[15]: $n^0 \rightarrow p^+ + e^- + \underline{\nu}^0$
2. Electron capture by a proton: $p^+ + e^- \rightarrow n^0 + \nu^0$
3. Positron emission by a proton (*i*): $\nu^0 + p^+ \rightarrow n^0 + e^+$
4. Positron emission by a proton (*ii*): $\gamma + p^+ \rightarrow n^0 + e^+ + \nu^0$

The latter two processes are very different[16] but yield the same: a proton emits a *positron* and becomes a neutron. However, the process we are interested in here is, of course, the positron emission which involves the photon absorption. So we think of a sequence like this:

1. The nucleus absorbs the gamma-ray photon by a proton-neutron *Verwandlung*[17]: $p^+ \rightarrow n^0 + e^+$. We have a proton less, but an extra neutron and a positron now.
2. The nucleus returns to its original state when the extra neutron decays back into a proton, *while emitting an electron*.[18] Hence, the equation is this:

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[14] See the values for the momentum in the final column of the PDG table.

[15] All of these processes involve neutrinos. We were first tempted to *not* distinguish between neutrinos and antineutrinos. We effective think of neutrinos as lightlike particles, so that is like photons, but involving a different force and, therefore, a different energy. Because they do not carry any charge (no electric and also no *strong* charge – or whatever else you might invent as a charge), the difference between neutrinos and antineutrinos must, therefore, be related to their spin only, which we interpret as being *physical* somehow (all of our theories are geometric and, therefore, *physical*). Spin is, therefore, always in one of two possible *geometric* directions, and the prefix (*anti*-) may, therefore, not be useful when talking neutrinos. We, therefore, opted to denote antineutrinos with an underscore ($\underline{\nu}^0$) instead of the usual overline ($\bar{\nu}^0$). It makes for easier typing too! 😊

[16] The first is the 1951 Cowan-Reines experiment (bombarding protons with neutrinos). The second describes β^+ decay. We refer to one of our papers on this for a more detailed description.

[17] We prefer this German word to the English: transformation. We admit it is not scientific. We note the proton-neutron transformation involves a neutrino. Where does that come from? We do not know: it may be energy from outside, but we think it should come from some internal *strong* field. We admit this is speculative. We put the neutrino in the final equation: the reader can verify we have it in both sides of the equation, which lends credibility to the hypothesis of using internal energy only here.

[18] Our accounting of neutrinos here is somewhat sloppy. We are not so worried about that. If the neutrinos are anti-neutrinos of each other, they should annihilate and provide some extra (strong) energy – whatever that might be. If not, then we would effectively need to keep track of them much more carefully than we do here. It should be noted that some of the other decay modes of neutral pions involve neutrinos. Hence, we do not feel our rather

$$\gamma + p^+ + \nu^0 \rightarrow n^0 + e^+ \rightarrow p^+ + e^- + e^+ + \nu^0$$

The *net* result is the $\gamma \rightarrow e^- + e^+$ equation that we needed. You will have to admit this is a much more elegant way to explain matter-antimatter pair production out of photons than the usual hocus-pocus, isn't it? However, science is not necessarily about elegance.[19] Science is about what makes sense and who does not. Hence, if this makes sense (which remains to be seen), we should also explain matter-antimatter annihilation in a way that shows *electric charge does not get magically lost somehow!* Let us see if we can do this.

Pair annihilation as a nuclear process

Let us think practically here too: the positron will meet an electron and there will be mutual annihilation but *where*, *exactly*? The positron is likely to meet an electron that is part of some atom. Will it engage with one of the electrons in the electrons shells? Maybe. However, if we would think of a neutron as consisting of a proton with an electron[20], we may imagine the positron to, perhaps, interact with the nucleus. Our positron is probably highly energetic and so it will, effectively, tear through the electron shells without any (meaningful) interaction with them or – more likely, perhaps – it may shear them all off without losing much energy at all.[21] Hence, we might imagine a process that is the *reverse* of the positron emission by a proton. Instead of $\nu^0 + p^+ \rightarrow n^0 + e^+$, we get this[22]:

$$n^0 + e^+ \rightarrow p^+ + \underline{\nu}^0$$

We might refer to this as *positron capture by a neutron*, and some scientific articles actually do explore this, although we are not sure whether or not there is some experimental evidence for this.[23] The question, of course, is this: how would a neutron *do* this?

We think of the neutron consisting of a proton and a neutron, in which case the incoming positron must annihilate the nuclear electron. Can we prove this? No. Can we rule out this is *not* possible? No. But we do think it makes a lot of sense.

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relaxed approach here (which basically amounts to saying that we might examine this more in detail later) as a serious issue. The reader has the right to disagree, of course. He may also want to think it through for himself by adding more detail to the analysis.

[19] As Dirac famously remarked, quantum field theory and perturbation approaches are surely *not* about elegance and beauty!

[20] The reader will, in the meanwhile, have understood that we love Rutherford's original hypothesis of the neutron combining a proton with *a nuclear electron*: we think it remains relevant and extremely productive. For a short introduction to Rutherford's ideas here, see our short history on quantum-mechanical ideas, in which we analyze some of Rutherford's remarks in this regard in his paper on '*The Structure of the Electron*' at the 1921 Solvay Conference.

[21] If we take the example of atmospheric molecules, the reader should remember those molecules are mostly ionized already, so there are no electron shells to start with even!

[22] Note that the *reverse* of the reaction involves an *anti*neutrino. Indeed, from a *mathematical* point of view, opposite spin and time reversal both amount to the same: the same wavefunction but with an opposite sign for the imaginary unit.

[23] A casual *google* effort yielded a list with an arXiv.org article: Mikhail Khankhasayev and Carol Scarlett, *Positron on Neutron capture reaction, radiative corrections and neutron electric dipole moment*, May 2013. However, this article is a theoretical exploration only. Theoretical as it is, it confirms the neutrino in the reaction must be an antineutrino, so that confirms our hypothesis.

So we lost a neutron and we gained a proton, but the state of the nucleus before and after must be the same – *sort of* at least, right? That is taken care of by the electron: we must assume this electron is highly energetic too and will, therefore, also be able to tear through the electron shells without any interaction.[24] This electron should be captured by a proton so as to restore the original nucleus state:

$$p^+ + e^- \rightarrow n^0 + \nu^0$$

So, yes, the two processes together yield the e^+e^- annihilation process we wanted to see:

$$\begin{array}{c} n^0 + e^+ \rightarrow p^+ + \underline{\nu}^0 \\ p^+ + e^- \rightarrow n^0 + \nu^0 \\ \hline \end{array}$$

$$p^+ + n^0 + e^+ + e^- \rightarrow p^+ + n^0 + \nu^0 + \underline{\nu}^0 \rightarrow p^+ + n^0 + 2\gamma$$

Note that the assumption here is that the neutrino and antineutrino will decay into *two* photons with opposite spin. How does this happen, *exactly?* That is a question we cannot answer for the time being. However, we feel it is more reasonable to argue that *strong* field energy inside of the nucleus could, somehow, be converted into electromagnetic field energy[25] – much more reasonable than the pointblank creation of matter-particles out of field energy, in any case!

The key point is this: this process explains matter-antimatter annihilation as a nuclear process too. There is, therefore, no need for quantum field theory ! 😊

Stable and unstable particles: equilibrium and non-equilibrium states

We have been talking about protons, neutrons, electrons, and their antimatter counterparts – *real* matter-particles. And about photons and – to a very limited extent – neutrinos. Things that we know to *exist* in any meaningful way: they last for a while, or even permanently (except when they happen to be part of a high-energy event, of course). So what *are* those pions, then?

You tell me. I do not worry about them too much. They are some kind of unstable state – a *disequilibrium* state, in other words: some *transient* electromagnetic oscillation[26] with one or more elementary charges whirling around in it. When a car gets destroyed in some accident, we are usually interested in the victims – not in the exact details of what debris flies where exactly. We are not, in any case. We summed up our vision of what makes sense in several ironic rewrites of Feynman's *Lectures*. We rewrote his introduction to quantum physics, for example, as follows[27]:

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[24] Note that the positron is going through a potential *well*, while the electron is going through a potential *barrier*.

[25] And vice versa, of course. The fourth reaction (photon absorption by a proton) which is so crucial in our reasoning here is actually a process which is not well understood. Instinctively, we feel it should, probably, also involve a photon-neutrino conversion, *somehow*. Because spin (angular momentum) is conserved, this probably involves *pair production* of photons and/or neutrinos. For a more profound analysis of what might or might not be going on in a nucleus, we may refer to our paper on protons and neutrons.

[26] You might wonder: perhaps some strong oscillation too? If you find it useful to think like that, I do not mind. Not at all, really. But I would appreciate if you could elaborate what you could possibly *mean* with that. Something neutrino-like, perhaps?

[27] See our Lectures on Physics, Chapter I: Quantum Behavior.

Newton thought that light was made up of particles, but then it was discovered that it behaves like a wave. Later, however (in the beginning of the twentieth century), it was found that light did indeed sometimes behave like a particle. Historically, the electron, for example, was thought to behave like a particle, and then it was found that in many respects it behaved like a wave. Hence, the challenge is to find a description that takes account both of the wave- as well as of the particle-like character of both matter- as well as light-particles. We may refer to both as wavicles but – for historical reasons – this term did not become household language.

Light-particles are known as photons. Photons carry electromagnetic energy, but they do *not* carry charge. In contrast, matter-particles always carry charge. If they are neutral – think of a neutron or an atom – they will carry both positive and negative charges. We should, therefore, think of them as composite particles. Elementary particles are stable. Composite particles consist of elementary particles and may be stable or unstable. An atom is an example of a stable composite particle. A neutron is stable inside of the nucleus but unstable as a free particle: it spontaneously disintegrates into a proton and an electron. This process involves the emission of a neutrino, which ensures energy is conserved. We think of a neutrino as a lightlike particle: it also carries energy but no charge.[28]

Electrons and protons are elementary matter-particles. They are stable because they are *wavicles* in an equilibrium state – in the sense that their *fundamental cycle* is given by the Planck-Einstein relation: $T = 1/f = h/E$.[29] They are stable but not indestructible. High-energy collisions between protons – or between protons and anti-protons – yield unstable particles which disintegrate back into stable particles. Because they are unstable, such particles should not be referred to as *particles* but as *transients* or, when very short-lived, as *resonances*.

The Higgs particle is an example of an extremely short-lived resonance: its lifetime is of the order of 10^{-22} seconds. Even at the speed of light – which an object with an estimated *rest* mass of 125 GeV/c^2 can never aspire to attain – it cannot travel any further than 0.3 *femto*meter (0.3×10^{-15} m) before it disintegrates. Such distance is *smaller* than the radius of a proton, which is in the range of 0.83 to 0.84 fm. Labelling it as a particle is, therefore, hugely misleading. Likewise, quarks have also never been directly observed or isolated. Their existence is and remains, therefore, a mere hypothesis, which we will not entertain in these lectures because we have no need for it: high-energy physics studies disintegration processes, which involve non-equilibrium states—and we will not study these in our lectures.[30] These high-energy collisions are interesting though because they show that protons must have some internal *structure*. We think of such structure not in terms of quarks or gluons[31], but in terms of the motion of the elementary charge. Paul Dirac wrote the following on that:

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[28] The *nature* of this energy is *not* electromagnetic, however. Electromagnetic energy is related to electromagnetic forces. We may, therefore, think of the energy of a neutrino as being related to the strong(er) force inside of a proton or a neutron.

[29] For a broad overview of our assumptions, which amount to a full-blown realist interpretation of particle or quantum physics, see our *Principles of Quantum Physics*.

[30] If you want to know what we think of the quark hypothesis, we think this hypothesis results from an unproductive approach to analyzing disintegration processes: Gell-Man and Kazuhiko Nishijima studied disintegration processes of K-mesons back in the 1950s, and invented new quantities that are supposedly being conserved in these processes. One of these quantities was referred to as strangeness (see the analysis of K-mesons in Feynman's *Lectures*). These strange new concepts then started to lead an even stranger life of their own.

[31] See our remarks on the quark hypothesis in footnote 30. As for gluons, these are supposed to carry the strong force. We see no need to invent new particles to carry forces: the concept of fields – electromagnetic or other – should do. The idea of force-carrying particles resembles 19th century *aether* theory: there is no need for it, so why should we entertain it?

> “Quantum mechanics may be defined as the application of equations of motion to particles. […] The domain of applicability of the theory is mainly the treatment of electrons and other charged particles interacting with the electromagnetic field—a domain which includes most of low-energy physics and chemistry.
>
> Now there are other kinds of interactions, which are revealed in high-energy physics and are important for the description of atomic nuclei. These interactions are not at present sufficiently well understood to be incorporated into a system of equations of motion. Theories of them have been set up and much developed and useful results obtained from them. But in the absence of equations of motion these theories cannot be presented as a logical development of the principles set up in this book.
>
> We are effectively in the pre-Bohr era with regard to these other interactions. It is to be hoped that with increasing knowledge a way will eventually be found for adapting the high-energy theories into a scheme based on equations of motion, and so unifying them with those of low-energy physics.”[32]

These words were written in 1958 but still ring true today. What about quantum field and perturbation theory? Dirac thought they could not be *true*.[33] We think the situation is a lot worse: no one seems to be able to clearly state why they were invented or what problem they are supposed to solve. It is probably a question to be left to the history of science: no one uses quantum mechanics in *practical* theory anyway. The study of semiconductors, for example, just takes the main results out of quantum physics and then develops more realist workable models based on these results.[34] In a *pragmatic* interpretation of what physics should and should not be, we think that is maybe not great (because untrue), but good enough (because practically workable). In addition, as Dr. Consa usefully notes[35], it sustains large research institutions and consumes budgets that would otherwise would probably be spent on R&D in the defense sector anyway. We may, perhaps, add a final remark on Dirac. In the *Preface* to the fourth and last edition (1958) of his *Principles of Quantum Mechanics* (1930) – from which we quote above – Dirac also writes this:

> “In present-day high-energy physics the creation and annihilation of charged particles is a frequent occurrence. A quantum electrodynamics which demands conservation of the number of charged particles is therefore out of touch with physical reality. So I have replaced it by a quantum electrodynamics which includes creation and annihilation of electron-positron pairs.
>
> This involves abandoning any close analogy with classical electron theory, but provides a closer description of nature. It seems that the classical concept of an electron is no longer a useful model in physics, except possibly for elementary theories that are restricted to low-energy phenomena.”

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[32] Paul A.M. Dirac, *The Principles of Quantum Mechanics*, 4th edition (1958), p. 312.

[33] In regard to Dirac’s skepticism, the Wikipedia article on Paul Dirac, quotes this from his last paper (*The inadequacies of quantum field theory*, 1984): "It effectively contains his last and final judgment on quantum field theory: "These rules of renormalization give surprisingly, excessively good agreement with experiments. Most physicists say that these working rules are, therefore, correct. I feel that is not an adequate reason. Just because the results happen to be in agreement with observation does not prove that one's theory is correct." The other quotes refer to the lack of a good theory, with a ‘good theory’ being defined as mentioned above: “a scheme based on equations of motion.” See our paper on the meaning of uncertainty and the geometry of the wavefunction.

[34] At least, that is what my son – who is currently finishing a master’s degree in engineering – tells me.

[35] See: *The Rotten State of QED*.

From what we wrote in this paper, the reader will understand we could not agree more with the former part of this statement. However, we do not agree with the latter part. We find Rutherford's concept of nuclear electrons (or neutrons combining a proton and an electron, *somehow*) amazingly productive and rich, and we think all that is needed to save the 'old quantum mechanics' is to think of pair creation and annihilation as *nuclear* processes – involving interactions with protons and neutrons, and also involving neutrinos. We may, therefore, qualify these interactions as *strong* rather than electromagnetic interactions, but such qualification is – for us, at least – not a license to multiply concepts by invoking color charges, quarks, gluons, or whatever other *virtual* particles one might come up with. We also think the classical concept of a field will do. The *quantization* of a field is a useful concept, but we think it has got nothing to do with fields condensing, somehow, in real or virtual (stable or not) particles.[36] We welcome good arguments on why we should think otherwise.

Conclusions

What new physics are we looking at, then? Probably some form of neo-classical physics: the old quantum physics *augmented* by a thorough exploration of what might be going on inside of a nucleus by further exploring Rutherford's idea of the nuclear electron, which joins one or more protons and provides the necessary attractive strong force to overcome the enormous electromagnetic forces which should push protons apart. Can we hope to uncover its structure? The challenge is to model the nucleus of deuterium: *deuteron.* We think of the neutron and the proton as two protons with an electron which – not unlike the valence electrons in some molecule – keep the cell together. Of course, trying to model how two positive and one negative elementary charge might be dancing together – combining not one but two very different forces (the electromagnetic force – which we know very well from what happens outside of the nucleus – and a strong(er) force, which we don't know at all) sounds endlessly much more complicated than the three-body problems you are used to.[37]

Can it be done at all? We are not sure. All we know is that not many have been trying since Bohr's young wolves hijacked scientific discourse after the 1927 Solvay Conference and elevated a mathematical technique – perturbation theory – to the scientific dogma which is now referred to as quantum field theory. In the meanwhile, we offer a few remarks in the annex which may or may not help to enlighten and/or focus the discussion some more. We also warmly recommend the work of Andrew Meulenberg on deep relativistic electrons (and/or electron deep orbits) and the related modeling of a neutron as an excited hydrogen state.[38]

Jean Louis Van Belle, 19 November 2020

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[36] See, for example, our analysis of quantized magnetic fields in the context of a ring current in a superconductor in our paper on the concept of a field. The quantization does not imply that we should assume that the magnetic field itself must, somehow, consist of (discrete) field quanta. Not at all. The magnetic field is just what it is: a finite quantized magnetic field.

[37] Note that, as far as we know, no general closed-form solution exists for the general three-body problem either! Is this a new form of quantum-mechanical uncertainty? To *not* add to the usual mystery-mongering, we would surely prefer to *not* use terms like this!

[38] Andrew Meulenberg and Jean-Luc Paillet, *Highly relativistic deep electrons and the Dirac equation*, Conference paper for the 22nd International Conference on Condensed Matter Science, Assisi (Italy), Sept 8-13 2019 (to be published in JCMNS).

Annex : Preliminary thoughts on a deuteron model

The electron *cloud* versus the proton *core*

The electron and the proton both incorporate the elementary charge. However, the *form factor(s)* in any model of an electron and a proton must be very different:

1. The electron appears as a pointlike charge whizzing around some center. The mass of this cloudlike object as a whole[39] is relatively small ($\mathrm{m_e} \approx 0.91{\times}10^{-30}\ \mathrm{kg}$) and the size of this *Zitterbewegung* (zbw) electron is given by its *Compton* radius[40] ($a_{\mathrm{C}} = \frac{\hbar}{\mathrm{m}c} \approx 386{\times}10^{-15}\ \mathrm{m}$).

Such *zbw* or *ring current* model[41] of an electron gives rise to a distinction between the electron itself and the *zbw* charge at its core, which has zero rest mass but – as it whizzes about at lightspeed – acquires a relativistic mass $\mathrm{m}_\gamma = \mathrm{m_e}/2$.[42] The orbital motion of the *zbw* charge inside generates the magnetic moment of the electron, and the small anomaly in the magnetic moment (of the order of Schwinger's $\alpha/2\pi$ factor) can be explained when assuming the *zbw* charge itself cannot be infinitesimally small: the calculations effectively yield the classical electron radius ($a_{\mathrm{e}} = \alpha \cdot a_{\mathrm{C}} \approx 2.82{\times}10^{-15}\ \mathrm{m}$). This, then, gives rise to the idea of an electron cloud, as opposed to the idea of a pointlike particle.[43]

2. A proton, in contrast, is (much) *more massive* and *much smaller*: its mass is about 1,836 times that of the electron ($\mathrm{m_p} \approx 1{,}673{\times}10^{-30}\ \mathrm{kg}$) and its radius was recently re-measured to be about $0.83 - 0.84{\times}10^{-15}\ \mathrm{m}$, which is about 3.35 times *smaller* than the classical electron radius, and about 460 times smaller than its Compton radius, which we think of as the effective *interaction* radius of a free electron.[44]

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[39] We interpret the mass of the electron as the inertia to a change in its state of motion in what is, essentially, an application of Wheeler's 'mass without mass' idea: the mass is the equivalent mass ($\mathrm{m} = \mathrm{E}/c^2$) of the energy in the motion of the pointlike charge. This mass combines (i) the energy in the oscillatory motion of the pointlike charge – which can be described using the elementary wavefunction ($\boldsymbol{r} = a \cdot e^{\pm i\theta}$, with the ± sign representing the basic spin direction), and (ii) its relativistic mass as a result of its velocity (c). For our electron model, see section 1-4 in our paper on quantum behavior.

[40] The Compton *radius* is the reduced Compton wavelength ($a_{\mathrm{C}} = \lambda_{\mathrm{C}}/2\pi$) which, paraphrasing Prof. Dr. Patrick LeClair, we effectively interpret as "the scale above which the electron can be localized in a particle-like sense."

[41] We use the two terms interchangeably, although Alfred Lauck Parson's original ring current model (1915) has very different incarnations, and *Zitterbewegung* theorists themselves – the most prominent of which is probably Dr. Hestenes – still struggle with various interpretations.

[42] The other half of the electron mass is in the field which keeps it going. Note that this is just one of the possible *interpretations* of the electron *Zitterbewegung*, which Schrödinger stumbled upon as a trivial solution to Dirac's wave equation for the free electron. For more background, see the paper mentioned in footnote .

[43] The term is usually reserved for electron in atomic or molecular orbitals, whose radius is of the order of the Bohr radius, which is related to the Compton radius by the same fine-structure constant ($r_{\mathrm{B}} = a_{\mathrm{C}}/\alpha$). However, which our model makes clear the term would be valid for a free electron as well. The $a_{\mathrm{e}} = \alpha a_{\mathrm{C}} = \alpha^2 r_{\mathrm{B}}$ relation gives rise to the interpretation of the fine-structure constant as a scaling constant. Some think of a fractal structure here (e.g. Oliver Consa, 2018), but such fractal structure is not consistent with the idea of a *zbw* charge with zero rest mass.

[44] The results of the 2019 PRad experiment yielded a point estimate of about 0.831 fm. While this value differs only slightly from the 0.841 value that was measured by Pohl (2010) and Antognini (2013), we think the PRad value is credible because it is very consistent with the anomalies (radius as well as magnetic moment) one can calculate using a ring current model. See our paper on anomalies, the fine-structure constant and the proton radius. As for

Hence, if we think of a neutron as, somehow, consisting of a proton and an electron, the picture which emerges is that of a proton in an electron cloud.

To the various *radii* of the electron – its radius as a pointlike charge (the hard core of a free electron), as a free electron, and as an electron in an atomic or molecular orbital – we should now, somehow, add the radius of an electron as a deep relativistic electron in the nucleus. That, then, is, briefly, the challenge that we are trying to highlight here.

Needless, to say, this new radius must be calculated from a force equation that, somehow, combines the electromagnetic as well as the strong force inside a nucleus and – so we believe – in the neutron itself. What can we say about the strong force? Apart from some very preliminary exploratory thoughts, nothing much.

For those preliminary thoughts, we refer to previous speculative thoughts[45]. Here, we will limit ourselves to a brief discussion of the idea that the proton might, perhaps, consist of charge that is being held together by the strong force. If so, a decent proton model might, perhaps, reveal the *geometry* or *structure* of the strong force.

The proton as a strong charge assembly?

One way of calculating electromagnetic mass is to assemble a uniform sphere of charge. This approach uses the Coulomb law only (electrostatics) and one wonders: might we think of using a different force formula – based on a model for the strong(er) force which, presumably, holds the proton together[46] – to determine some kind of 'strong' mass (as opposed to electromagnetic mass) for the proton?

We refer to Feynman's calculations of the necessary integral[47] for the electrostatic force, which yields the following formula for a sphere of radius *a* with total charge Q:

$$\mathrm{U} = \frac{3}{5}\frac{\mathrm{Q}^2}{4\pi\epsilon_0 a} \Leftrightarrow a = \frac{3}{5}\frac{\mathrm{Q}^2}{4\pi\epsilon_0 \mathrm{U}}$$

Substituting Q for the elementary charge, and U for the total energy of the electron, we get:

$$a = \frac{3}{5}\frac{\mathrm{q}_\mathrm{e}^2}{4\pi\epsilon_0 \mathrm{m}_\mathrm{e} c^2} = \frac{3}{5}a_\mathrm{e} = \frac{3}{5}\alpha a_\mathrm{C} = \frac{3}{5}\alpha\frac{\hbar}{\mathrm{m}_\mathrm{e} c}$$

We get a rather annoying 3/5 factor here. In a later lecture devoted to electromagnetic mass only[48], Feynman tries one or two different definitions of electromagnetic mass in an attempt to explain this, but admits he fails and concludes the electromagnetic mass model does not work for an electron. We are not so sure: a 3/5 factor is not nice, but it is pretty good, isn't it? At least we get the correct order of

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the difference between a charge and an interaction radius, this should speak for itself but the reader may want to review their agreed definitions.

[45] See, for example, our papers on the nature of Yukawa's charge and force, which also offer some speculative thoughts on a possible wave equation for the strong force.

[46] When applying a simple ring current model for the proton, one can calculate the centripetal force that would be needed to hold the pointlike charge in orbit: the calculations yield a rather astonishing value (about 89,349 N, to be precise) in comparison to the calculations of the centripetal force inside of the electron (0.106 N). See footnote 42 for the reference.

[47] See : Feynman's *Lectures*, Vol. II, Chapter 8, section 1.

[48] See: Feynman's Lectures, Vol. II, Chapter 28, Electromagnetic mass.

magnitude and – who knows? – perhaps some formula allowing for a varying charge density might solve the problem!

However, we should keep our wits about us here! It is actually not the 3/5 factor but the fine-structure constant which is annoying here! That is a much more annoying factor in this context: we are wrong by a factor which is approximately equal to (3/5)·(1/137) now! In fact, this charge assembly model of an elementary particle would fit a proton much better than an electron *because our cloud model of an electron assumes a pointlike charge with zero rest mass*. In contrast, our proton is *not* cloudlike and, hence, a charge assembly model based on some 'strong' force would make sense, right?[49]

[…]

Maybe. Maybe not. Probably not. We should not forget we want to explain why things stay together—not why they fall apart! Hence, a deuteron model should probably more think in terms of modeling a strong force between *opposite* charges: the two protons being held together by a nuclear electron. This is, in fact, the basic idea behind the new deuteron model which we hope will be found one day: it would confirm that one should effectively think of a neutron as consisting of a proton with a nuclear electron: no quarks, no gluons!

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[49] We developed a ring current model for the proton in previous papers, but we now feel it raises as many questions as it answers. See, for example, our paper on the mass, radius and magnetic moment of electrons and protons.