The Charge Conservation Principle and Pair Production

The creation of an electron-positron pair out of a highly energetic photon – the most common example of pair production – is often presented as an example of how energy can be converted into *matter*. Vice versa, electron-positron annihilation then amounts to the *destruction* of matter. However, if John Wheeler's concept of 'mass without mass' is correct – read: if Schrödinger's trivial solution to Dirac's equation for an electron in free space (the *Zitterbewegung* interpretation of an electron) is correct – then what happens is far more intriguing.

John Wheeler's intuitive idea is that matter and energy are just two sides of the same coin. That was Einstein's intuition too: mass is just a measure of inertia—a measure of the resistance to a change in the state of motion. Energy itself is motion: the motion of a *charge*. In this interpretation of physics, an electron is nothing but a pointlike charge whizzing about some center. The pointlike charge has zero rest mass, which is why it moves about at the speed of light.[1] The electron model is easy and intuitive. Developing a similar model for a *nucleon* – a proton or a neutron – is much more complicated because nucleons are held together by another force, which we commonly refer to as the strong force.

In regard to the latter, the reader should note that I am very hesitant to take the quark-gluon model of this strong force seriously. I entirely subscribe to Dirac's rather skeptical evaluation of it:

> "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."[2]

I readily admit he wrote this in 1967, reacting, most probably, to the invention of a new conservation law (the conservation of *strangeness*, as proposed by Gell-Mann, Nishijima, Pais and others) and the introduction of many other *ad hoc* QCD quantum numbers to explain why this or that disintegration

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[1] Erwin Schrödinger stumbled upon the *Zitterbewegung* interpretation of an electron when he was exploring solutions to Dirac's wave equation for free electrons. It's worth quoting Dirac's summary of it: "The variables give rise to some rather unexpected phenomena concerning the motion of the electron. These have been fully worked out by Schrödinger. It is found that an electron which seems to us to be moving slowly, must actually have a very high frequency oscillatory motion of small amplitude superposed on the regular motion which appears to us. As a result of this oscillatory motion, the velocity of the electron at any time equals the velocity of light. This is a prediction which cannot be directly verified by experiment, since the frequency of the oscillatory motion is so high and its amplitude is so small. But one must believe in this consequence of the theory, since other consequences of the theory which are inseparably bound up with this one, such as the law of scattering of light by an electron, are confirmed by experiment." (Paul A.M. Dirac, *Theory of Electrons and Positrons*, Nobel Lecture, December 12, 1933)

[2] P. A. M. Dirac, *The Principles of Quantum Mechanics*, Oxford University Press, 4th revised edition, Chapter XII (Quantum Electrodynamics), p. 312.

path does or does not occur. It was all part of the Great Sense-Making Exercise at the time: how to explain the particle zoo?[3] In short, I am very reluctant to take the quark-gluon model of the strong force seriously.

However, I do acknowledge the experimental discovery of the fact that pairs of matter and anti-matter particles could be created out of highly energetic photons may well be the most significant discovery in post-WW II physics. Dirac's preface to the 4th edition of the *Principles of Quantum Mechanics* summarized this as follows:

> "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. […] 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."

Having said this, I think it's useful to downplay Dr. Dirac's excitement somewhat. Our world is governed by low-energy phenomena: if our Universe was created in a Big Bang – some extremely high-energy environment – then it happened 14 billion years or so ago, and the Universe has *cooled down* since. Hence, these high-energy experiments in labs and colliders are what they are: high-energy collisions followed by disintegration processes. They emulate the conditions of what might have happened in the first second – or the first minute, perhaps (surely *not* the first day or week or so) – after Creation.[4]

I am, therefore, a bit puzzled by Dr. Dirac's sentiment. Why would he think the classical concept of an electron is no longer useful? An electron is a permanent fixture. We can create and destroy it in our high-energy colliders, but that doesn't mean it's no longer useful as a concept.

Pair production only happens when the photon is fired into a nucleus, and the generalization to 'other' bosons 'spontaneously' disintegrating into a particle and an anti-particle is outright pathetic. What happens is this: we fire an enormous amount of electromagnetic energy into a nucleus (the equivalent mass of the photon has to match the mass of the electron and the positron that's being produced) and, hence, we destabilize the stable nucleus. However, Nature is strong. The strong force is strong. Some intermediate *energy state* emerges but Nature throws out the spanner in the works. The end result is that all can be analyzed, once again, in terms of the Planck-Einstein relation: we have stable particles, once again. [Of course, the positron finds itself in the anti-Universe and will, therefore, quickly disappear in the reverse process: electron-positron annihilation.]

No magic here. And – surely – no need for strange QCD quantum numbers.

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[3] Feynman's 1963 *Lecture* on K-mesons (http://www.feynmanlectures.caltech.edu/III_11.html#Ch11-S5) is an excellent summary of the *state of affairs* at the time. The new colliders had, effectively, generated a 'particle zoo', and it had to be explained. We think physicists should first have acknowledged that these short-lived particles should, perhaps, not be associated with the idea of a (fundamental) particle: they're unstable. Transients, at best. Many of them are just resonances.

[4] I use the term 'Creation' as an absolutely non-religious concept here: it's just a synonym of the presumed 'Big Bang'. To be very clear on this, I am rather appalled by semi-scientific accounts of the creation of our world in terms of the biblical week.