The concept of a field

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18 October 2020
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Summary

This paper explores the commonly used concept of a field and the concept of quantization of fields. We do so by discussing the quantization of *traveling* fields using our photon model, and we also look at the quantization of fields in the context of a perpetual ring current in a superconductor. A second (future) version of this paper should be more elaborate.

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Introduction

I do not know where to start this story. I am also not quite sure for whom I am writing it. For people like me, obviously: most of what we do, we do for ourselves, right? So I should probably describe myself in order to describe the audience: amateur physicists in the epistemology of modern physics – or its ontology, or its metaphysics. I also talk about the genealogy or archaeology of ideas on my ResearchGate site. All these words have (slightly) different meanings but the distinctions do not matter all that much. The point is this: I write for people who want to *understand* physics in pretty much the same way as the great classical physicist Hendrik Antoon Lorentz who, just a few months before his demise, at the occasion of the (in)famous 1927 Solvay Conference, wanted to understand the 'new theories':

> "We are representing phenomena. We try to form an image of them in our mind. Till now, we always tried to do using the ordinary notions of space and time. These notions may be innate; they result, in any case, from our personal experience, from our daily observations. To me, these notions are clear, and I admit I am not able to have any idea about physics without those notions. The image I want to have when thinking physical phenomena has to be clear and well defined, and it seems to me that cannot be done without these notions of a system defined in space and in time."

Note that H.A. Lorentz understood electromagnetism and relativity theory as few others did – as few others do today still, so he should surely not be thought of as a classical physicist who, somehow, was stuck. On the contrary: he probably understood the 'new theories' better than many of the new theorists themselves. In fact, as far as I am concerned, I think his comments or conclusions on the epistemological status of the Uncertainty Principle – which he made in the same intervention – still stand. Let me quote the original French:

> "Je pense que cette notion de probabilité [in the new theories] serait à mettre à la fin, et comme conclusion, des considérations théoriques, et non pas comme axiome *a priori,* quoique je veuille bien admettre que cette indétermination correspond aux possibilités expérimentales. Je pourrais toujours garder ma foi déterministe pour les phénomènes fondamentaux, dont je n'ai pas parlé. Est-ce qu'un esprit plus profond ne pourrait pas se rendre compte des mouvements de ces électrons. Ne pourrait-on pas garder le déterminisme en en faisant l'objet d'une croyance? *Faut-il nécessairement ériger l' indéterminisme en principe*?"

What a beautiful statement: **why should we elevate indeterminism to a philosophical principle?** Indeed, now that I have inserted some French, I may as well inject some German. The idea of a particle includes the idea of a more or less well-known position. Let us be specific and think of uncertainty in the context of position. We may not fully know the position of a particle for one or more of the following reasons:

1. The precision of our measurements may be limited: this is what Heisenberg referred to as an *Ungenauigkeit*.
2. Our measurement might disturb the position and, as such, cause the information to get lost and, as a result, introduce an uncertainty: this is what we may translate as an *Unbestimmtheit*.
3. The uncertainty may be inherent to Nature, in which case we should probably refer to it as an *Ungewissheit*.

So what is the case? Lorentz claims it is either the first or the second – or a combination of both – and that the third proposition is a philosophical statement which we can neither prove nor disprove. I cannot see anything logical (theory) or practical (experiment) that would invalidate this point. I, therefore, intend to write a basic book on quantum physics from what I hope would be Lorentz' or Einstein's point of view.

My detractors will immediately cry wolf: Einstein lost the discussions with Bohr, didn't he? I do not think so: he just got tired of them. I want to try to pick up the story where they have left it.

Space and the vacuum

Modern physicists have multiplied concepts and do not shy away from confusing language: spacetime oscillations, virtual particles and quantum fields are just a few of the wonderful new words. They are unscientific, either because there is no agreement on their exact meaning or, else, because one cannot measure them. Space may well be the most ambiguous term of all. If it is empty, we say it is the vacuum, but physicists will still endow it with physical qualities or – worse – assume it is actually *not* empty. Let me quote Robert B. Laughlin, a Nobel Laureate in Physics, here:

> "It is ironic that Einstein's most creative work, the general theory of relativity, should boil down to conceptualizing space as a medium when his original premise [in special relativity] was that no such medium existed [..] The word 'aether' has extremely negative connotations in theoretical physics because of its past association with opposition to relativity. This is unfortunate because, stripped of these connotations, it rather nicely captures the way most physicists actually think about the vacuum."

Most physicists effectively think like that, but I think we should reserve the term vacuum for a true vacuum: a truly empty space. We will *represent* it, in our mind, by a Cartesian 3D space: so the vacuum *corresponds* to a purely mathematical space, but it is real – or physical, if you want – because we can put real stuff in it. In fact, a true vacuum does not exist: space – real space – is filled with light and matter. Light is radiation – everything from low-energy radio waves to particle-like gamma rays – and matter is matter: protons and electrons, basically, and their antimatter counterparts, of course. Matter-particles carry (electric) charge. Light does not: it carries energy, but no charge. We will come back to this. Let us first say a few words about fields.

What fields? Electric fields, magnetic fields, and gravitational fields, of course. Fields are *real* too, and it looks like they are usually *quantized* too. However, that does not necessarily mean we should imagine them as a bunch of *virtual* particles. In fact, I think we should *not*, because there is no reason to: we do not need the concept of virtual particles to make sense of the physical world. Let us dive into it all by jotting down some formulas and, more importantly, *interpreting* them as part of what I refer to as a *realist* interpretation of quantum mechanics, which is an explanation in terms of a system defined in space and in time – as H.A. Lorentz wanted it! So here we go.

Fields and photons

In classical electromagnetic theory, light is modeled as a traveling electromagnetic field, but quantum physics tells us light consists of particles: photons. So how should we imagine them, and how are they different from, say, an electric or magnetic field *tout court*? Let us start with the latter. We will write an electric or magnetic field as $\boldsymbol{E}(x, y, z, t)$ and $\boldsymbol{B}(x, y, z, t)$ respectively. It may be static or dynamic. If it is static, then ***E*** and ***B*** are a function of the position ***x*** = (*x*, *y*, *z*) only: the time variable is irrelevant because they do not vary with time. Real-life fields are more likely to be dynamic: they become stronger or weaker, for example.

Now, you may think a photon is something like a dynamic electromagnetic field, but it is quite particular – at least that is what I think! A photon is a *traveling* field, so the electromagnetic field is zero everywhere, except at the very spot where our photon happens to be. That is what makes the photon pointlike: the field vectors ***E*** and ***B*** that describe it will be zero at each and every point in time and in space *except if our photon happens to be at **x** = (x, y, z) at time t.*

Of course, we also know that a photon is defined by its *wavelength*, so how does that work? What is the *physical* meaning of the wavelength? It is, quite simply, the distance over which the electric and magnetic field vectors will go through a full *cycle* of their oscillation. That is all there is to it: nothing more, nothing less. Let me be very explicit about this – because I want to make sure we start off on the right foot.

The wavelength is a *linear* distance, of course. To be precise, it is the distance Δs between two points (x_1, y_1, z_1) and (x_2, y_2, z_2) where the ***E*** and ***B*** vectors have the same value. The photon will need some time Δt to travel between these two points, and these intervals in time and space are related through the (constant) velocity of the wave, which is also the velocity of the pointlike photon. That velocity is, of course, the speed of light, and the time interval is the cycle time T = 1/*f*. We, therefore, get the equation that should be familiar to you:

$$c = \frac{\Delta s}{\Delta t} = \frac{\lambda}{\mathrm{T}}$$

We can now relate this to the Planck-Einstein relation E = $h \cdot f = \hbar \cdot \omega$, which you should think of as the most important equation in all of quantum physics. Indeed, the Planck-Einstein relation relates *f* and T to the energy (E) through Planck's constant (*h*):

$$\mathrm{E} = h \cdot f = \hbar \cdot \omega \Leftrightarrow \mathrm{E} \cdot \mathrm{T} = h$$

Think of the photon as *packing* not only the energy E but also an amount of *physical action* that is equal to $h \approx 6.626 \times 10^{-34}$ N·m·s. The concept of *physical action* is a concept whose meaning, for some reason I do not quite understand, is not often discussed. Here again, the original German term for it – a *Wirkung* – may capture our imagination much better. Let us explore the meaning of Planck's *quantum of* (physical) *action* by further developing our photon model. Physical action can *express* itself in two ways: as some energy over some time (E·T) or – alternatively – as some momentum over some distance (p·λ). Indeed, we know that the (pushing) momentum of a photon[1] will be equal to p = E/*c*. We can, therefore, write the Planck-Einstein relation for the photon in two equivalent ways:

$$\mathrm{E} \cdot \mathrm{T} = \frac{E}{c} \cdot c\mathrm{T} = h \Leftrightarrow \mathrm{p} \cdot \lambda = h$$

We could jot down many more relations, but we should not be too long here.[2] We said the photon *packs*

[1] For an easily accessible treatment and visualization in space, as well as the calculation of the formula itself, see: *Feynman's Lectures*, Vol. I, Chapter 34, section 9.

[2] We may refer the reader to our manuscript, our paper on the meaning of the fine-structure constant, or various

an energy that is given by its frequency (or its wavelength or cycle time through the $c = \lambda f$ relation) through the Planck-Einstein relation. We also said it packs an amount of *physical action* that is equal to h. So how should we think of that? Let us connect a few more dots here.

The Planck-Einstein relation does not only apply to a photon, but it also applies to electron orbitals—but in a different way: the Planck-Einstein tells us electron orbitals are also separated by an amount of *physical action* that is equal to $h = 2\pi\cdot\hbar$.[3] Hence, when an electron jumps from one level to the next – say from the second to the first – then the atom will lose one unit of h. As mentioned above, that is the amount of physical action which our photon will also have to pack that somehow. It will also have to pack the related energy, which is given by the Rydberg formula:

$$\mathrm{E}_{n_2} - \mathrm{E}_{n_1} = -\frac{1}{{n_2}^2}\mathrm{E}_R + \frac{1}{{n_1}^2}\mathrm{E}_R = \left(\frac{1}{{n_1}^2} - \frac{1}{{n_2}^2}\right)\cdot \mathrm{E}_R = \left(\frac{1}{{n_1}^2} - \frac{1}{{n_2}^2}\right)\cdot \frac{\alpha^2 \mathrm{m}c^2}{2}$$

To focus our thinking, let us consider the transition from the second to the first level, for which the $1/n_1^2 - 1/n_1^2$ factor is equal 0.75. Hence, the photon energy should be equal to $(0.75)\cdot\mathrm{E}_R \approx 10.2$ eV. Now, if the total action is equal to h, then the cycle time T can be calculated as:

$$\mathrm{E}\cdot\mathrm{T} = h \Leftrightarrow \mathrm{T} = \frac{h}{\mathrm{E}} \approx \frac{4.135\times 10^{-15}\mathrm{eV}\cdot\mathrm{s}}{10.2\ \mathrm{eV}} \approx 0.4\times 10^{-15}\ \mathrm{s}$$

This corresponds to a wave train with a length of $(3\times10^8$ m/s$)\cdot(0.4\times10^{-15}$ s$) = 122$ nm. It is, in fact, the wavelength of the light ($\lambda = c/f = c\cdot\mathrm{T} = \mathrm{h}\cdot c/\mathrm{E}$) that we would associate with this photon energy.

What if an electron transitions from a higher level? The reasoning remains the same, but the photon will still pack *one* unit of *h* only: we will let you think this through for yourself as an exercise.

Now, if you think all of the above is rather trivial, then that is good: just consider it as a warm-up for the math that follows. If not, then it is also good: it then means it was useful to take you through this. At this point, we might also make some remarks in regard to the *spin* of a photon, but we will leave that for later. Indeed, as we are still introducing stuff, it is more useful at this point to contrast this photon model with the idea of (non-traveling) electric or magnetic fields.

The quantization of fields

Matter-particles – electrons, for example – are, obviously, discrete. In the previous section, we also showed the particles of light – photons – are discrete or pointlike as well, albeit in a rather special way:

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others papers in which we explore the nature of light. We just like to point out one thing that is quite particular for the photon: the reader should note that the $\mathrm{E} = \mathrm{m}c^2$ mass-energy equivalence relation and the $\mathrm{p} = \mathrm{m}c = \mathrm{E}/c$ can be very easily related when discussing photons. There is an easy *mathematical* equivalence here. That is not the case for matter-particles: the *de Broglie* wavelength can be interpreted geometrically but the analysis is somewhat more complicated—not impossible (not at all, actually) but just a bit more convoluted because of its circular (as opposed to linear) nature.

[3] The model of the atom here is the Bohr model. It does *not* take incorporate the finer structure of electron orbitals and energy states. That finer structure is explained by differences in magnetic energies due to the *spin* (angular momentum) of the electron. We will come back to this. Also note we take the most general of cases: a photon being emitted or absorbed by an atom. Photons can also be (briefly) absorbed and emitted by free electrons in an excited state: this usually involves a change in wavelength and an equivalent change in the kinetic energy of the electron (Compton scattering).

when a photon hits the detector, *all* of the energy is absorbed. Hence, one obtains the energy from integrating over the whole wavelength.[4] What if we have fields but no light – no radiation? Does such situation exist?

It surely does. A good example is the magnetic field that is trapped by a superconducting ring. There is no heat there: no *thermal* motion of electrons, nuclei or atoms or molecules as a whole and, therefore, no (heat) *radiation*. Also, the perpetual currents in a superconductor behave just like electrons in some electron orbital in an atom: they do *not* radiate their energy out. In fact, that is why superconductivity is said to be a quantum-mechanical phenomenon which we can effectively observe at the *macroscopic* level. Hence, we have a magnetic field but no radiation[5] and, since 1961 (the experiments by Deaver and Fairbank in the US and, independently, by Doll and Nabauer in Germany), we know this field is quantized. To be precise, the product of the charge (q) and the magnetic flux (**Φ**), which is the product of the magnetic field *B* and the area of the loop *S*, – will always be an integer (*n*) times *h*[6]:

$$q \cdot \mathbf{\Phi} = q \cdot B \cdot S = n \cdot h$$

However, this rather brief example shows there is absolutely no need whatsoever to assume that the magnetic field itself must, somehow, consist of (discrete) *field quanta*. It is just what it is: a finite quantized magnetic field. There is absolutely no need whatsoever to think of virtual particles or whatever other nonsense here.

We should note another thing here: the equation above makes it clear the field cannot be separated from the circulating charge which – because electrons form Cooper pairs in superconductors – is *twice* the electron charge, which explains why the basic flux unit can be defined as:

$$\phi_0 = \frac{h}{2q_e}$$

Finally, we should make another simple but interesting calculation here. We have a circular current and this current loop will have a magnetic moment (μ) equal to the product of the current and the surface area of the loop: $\mu = I \cdot \pi \cdot a^2 = I \cdot S$. Of course, the current in such loop is equal to the charge times the frequency of the orbit ($I = q \cdot f$), so we can re-write the magnetic moment as $\mu = q \cdot f \cdot S$. Now, we also know the (potential) magnetic *energy*[7] is calculated as the product of the magnetic moment and the magnetic

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[4] It may take the reader a while to combine the ideas of a photon being pointlike and having a linear wavelength at the same time, but there is no contradiction.

[5] The critical reader will immediately note we do need photons to *observe* what is going on (think of [one of the many videos showing magnetic levitation here]). That is, obviously, true, but these photons – this light – goes in and out and does not affect the perpetual current because of the Meissner effect: when a metal becomes a superconductor, it will expel all fields. Other remarks may be made, but we will limit ourselves here to a rather rudimentary description of the fundamentals.

[6] $\Phi = \mathbf{B} \cdot \mathbf{S}$ is a *vector* (dot) product but – because of the set-up – reduces to an ordinary scalar product: $\Phi = \boldsymbol{B} \cdot \boldsymbol{S} = |\mathbf{B}||\mathbf{S}|\cos\theta = B \cdot S$. As usual, it is always instructive to check the physical dimensions: the magnetic field is expressed in N/C times s/m, while the surface area is expressed in m^2. Hence, $[q \cdot B \cdot S] = C \cdot (N/C) \cdot (s/m) \cdot m^2 = N \cdot m \cdot s$, which is effectively the physical dimension of Planck's quantum of action.

[7] The formula should take the directions of the magnetic moment and the magnetic field into account and is, therefore, a vector dot product: $U_{mag} = -\boldsymbol{\mu} \cdot \mathbf{B}$. In fact, the magnetic moment and the magnetic field are aligned here, and this vector product should, therefore, be zero. We are, therefore, probably talking *potential* rather than

field: $U_{mag} = \mu \cdot B$. We can, therefore, show that the Planck-Einstein relation is valid here again. Indeed, the (magnetic) energy is an integer multiple of Planck's constant times the frequency of the current:

$$\mathrm{E} = \mathrm{U_{mag}} = \mu \cdot \mathrm{B} = \mathrm{q} \cdot f \cdot \mathrm{S} \cdot \frac{n \cdot h}{\mathrm{q} \cdot \mathrm{S}} = n \cdot h \cdot f$$

While the formula is very straightforward, its interpretation is much less so. First, we should note that we should take the directions of the magnetic moment and the magnetic field into account. The energy is, therefore, a vector dot product: $U_{mag} = -\boldsymbol{\mu}\cdot\mathbf{B}$. In fact, the magnetic moment and the magnetic field are aligned here, and this vector product should, therefore, be zero. Also, the use of the $U_{mag} = -\boldsymbol{\mu}\cdot\mathbf{B}$ formula assumes some *external* magnetic field: a very different magnetic field '**B**', in other words. We are, therefore, probably calculating some kind of *potential* rather than actual energy here, and we should, therefore, probably try to analyze the set-up as an oscillation in two dimensions – in line with the oscillator model we developed for electrons.

Secondly, it would probably be useful to relate the frequency to the *velocity* of the charge so as to possibly further simplify or interpret this result. Unfortunately, quantum physics does not busy itself with this question, so we have to leave it open for the time being.[8]

A final question concerns the spatial distribution of the magnetic field. As can be seen from the illustration below (taken from Feynman's *Lectures*, III-21-7) the magnetic field is quite local – but the question is: how local, *exactly*?

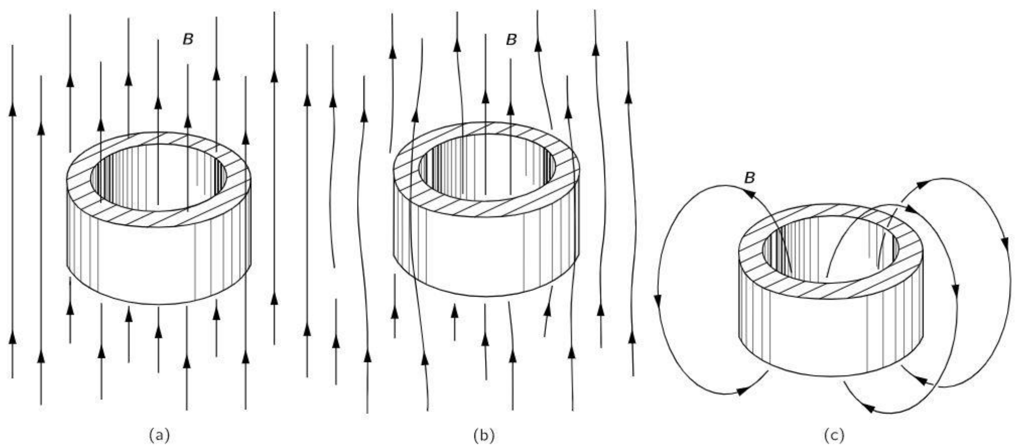

Figure 1: A ring in a magnetic field: (a) in the normal state; (b) in the superconducting state (Meissner effect pushes external fields out; (c) after the external field is removed.

In regard to our last question – spatial extent of such magnetic fields – I should probably further explore a rather enigmatic remark, made by H.A. Lorentz – once more ! – at the occasion of the 1921 Solvay Conference, while discussing the ring current model of an electron:

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actual energy and we should, probably, analyze the set-up as an oscillation in two dimensions – in line with the oscillator model we developed for electrons.

[8] We refer the reader to one of our recent papers (Matter-waves, amplitudes and signals) for an initial exploration of this issue.

> "The idea of a rotating ring [in French: *anneau tournant*] has a great advantage when trying to explain some issues [in the theory of an electron]: **it would not emit any electromagnetic radiation. It would only produce a magnetic field in the immediate space that surrounds it.** [...]" (H.A. Lorentz, 1921 Solvay Conference, boldface and italics added)

This shows, once again, the value of analyzing a superconducting ring so as to learn more about the (possible) structure of an electron. In any case, while we are pointing to various other research questions here, the gist of the matter remains the same: at no point in the analysis is there a need to think that the field, while quantized, should, somehow, consist of discrete *field quanta* in space. There is, therefore, no need to invoke quantum field theory or the existence of virtual particles.

Why, then, did quantum physicists go this way after WW II?

We honestly have no idea. We wrote about Yukawa's contribution to quantum physics last year[9], and we do not think we should add anything to that.

Conclusion(s)

We will further explore the concept of fields in a second version of this paper but, as for now, we may already offer some salient remarks:

1. Fields are real: they are *relative*, of course – as relative as energy or momentum – but they are equally real.
2. There is, as yet, no reason to assume fields are not discrete. On the contrary, they seem to be continuous. As such, they effectively fill the vacuum.
3. Fields are not to be confused with light-like particles – photons and, in our particular interpretation of quantum physics[10] – neutrinos. We may think of them as *traveling* fields but this confuses rather than explains the difference with the concept of static and/or dynamic fields as used in most analyses.

Jean Louis Van Belle, 18 October 2020

[9] See: The Nature of Yukawa's Nuclear Force and Charge, followed by: Who Needs Yukawa's Wave Equation? (June 2019).

[10] See our Principles of Quantum Physics (June 2020).