Towards a Better Understanding of the Electron's Magnetic Moment: A Reply to Sanchioni

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Abstract

In this short article, I seek to clarify some of the broader motivations and ambitions guiding my work on electron spin. I respond to Sanchioni (Found. Phys. **55**(67), 2025), who has criticized my recent study of the electron's anomalous magnetic moment (Sebens in Found. Phys. **55**(48), 2025). I argue against viewing quantum field theory instrumentally as merely "an architecture of consistent predictions" and in favor of explaining physical phenomena using descriptions of what is actually out there in nature. I defend the importance of asking how the move from the Dirac equation (with self-interaction) to quantum field theory takes you from a variable to fixed magnetic moment, emphasizing my agreement with Sanchioni that the Dirac equation yields only a flawed model of the electron. I explain that quantum field theory, as it stands, is incomplete, and discuss how we might be able to arrive at a better explanation of the electron's anomalous magnetic moment.

Contents

1 Introduction

The electron's spin magnetic moment can be predicted very accurately within quantum field theory. The simpler Dirac equation is normally described as missing a small correction: the electron's anomalous magnetic moment. In [1], I revisit the Dirac equation to ask what spin magnetic moment we ought to expect in that context if we incorporate both self-interaction and mass renormalization. I find that once those effects are included, the magnetic moment[1] that is generated by the rotation of charge [1–7] is no longer fixed. It depends on the particular state of the electron. I conclude by posing a question: How does the move from the Dirac equation to quantum field theory take the magnetic moment from variable to fixed?

In [8], Sanchioni questions the purpose of such work and argues that quantum field theory can perfectly well explain the electron's fixed magnetic moment without having to provide a visualizable model of the electron. Here, I respond.

2 Ontology and Explanation

The debate between Sanchioni and I about the electron's magnetic moment is a small skirmish in a larger war about how physics should be taught and practiced. Sanchioni and I agree that modern physics can often generate accurate predictions without providing a clear picture as to what is actually happening in nature. Sanchioni embraces this feature of modern physics, whereas I see it as a problem to be fixed. Sanchioni [8, p. 9] worries that my project

> "risks pedagogical regression: by offering an apparent mechanical 'cause,' it suggests that QED [(quantum electrodynamics)] is somehow incomplete, or that its success demands visualization in classical terms. Such framing can mislead students and philosophers alike into searching for mechanistic underpinnings where none are needed or appropriate. The epistemic virtue of modern physics often lies precisely in its ability to explain without picturing."

The pedagogy of physics is indeed at stake and I think that the path to pedagogical *progression* is through recognizing that QED is incomplete and attempting to fill it in with a specific proposal as to what is actually happening in nature (though not necessarily in "classical terms").

According to Sanchioni [8, p. 7], QED "provides not a picture, but a structure; not an image of the electron, but an architecture of consistent predictions." That "architecture of consistent predictions" includes equations that can be used to calculate the electron's anomalous magnetic moment to high precision.[2] Sanchioni takes this

[1] Here and after I drop the "spin" in "spin magnetic moment."

[2] Higher precision can be achieved by appealing to the entire standard model. But, here we can focus our attention on QED.

instrumentalist approach to be sufficient for fully explaining the electron's anomalous magnetic moment. According to Sanchioni [8, p. 9], "explanation can reside in the structural, symmetry-based architecture of a theory, even when it defies direct visualization." We do not need to know what the electron actually is, or how that thing behaves, to understand the strength of its magnetic moment. In the last line of his paper, Sanchioni emphasizes "the philosophical need to resist nostalgia for visualizable models when confronting the abstract architecture of quantum reality."[3]

By contrast, I think we should be guided by the nostalgia that Sanchioni maligns. Physical theories used to come with explicit, visualizable models of reality, and we should seek such models to accompany the theories of modern physics. Developing and comparing possible models of reality can bring us closer to understanding what is really happening in nature and can also yield other kinds of progress: simplifying calculations, suggesting new applications, improving pedagogy, or inspiring new directions for future physics.

This is not to say that we need to find models to make progress. Much can be done without a clear model of reality, as the history of quantum physics shows. Accurate predictions can be made, and explanations can be found. In particular, the structural explanations that Sanchioni describes are available. These structural explanations are valuable and can have impressive breadth, applying across different theories and/or different ways of filling in the ontology for a given theory (the ontology being the things that exist and are governed by the laws of the theory).[4] This breadth is a virtue if you want to remain agnostic about the underlying ontology for a given theory, or if you are seeking a general explanation that applies across a set of similar theories. However, such structural explanations are inevitably incomplete.

To fully understand a particular physical phenomena, I believe that we must find an explanation in terms of the theory's laws and ontology [11–15]. Sanchioni [8, p. 7] accurately characterizes my ambitions:

> "Sebens's proposal is not merely technical. It is motivated by a broader philosophical aim: to recover physical insight in a domain where calculations often obscure interpretation. ... In particular, Sebens appears to seek an ontologically grounded account of the electron's anomalous magnetic moment—one that explains it not merely through the mathematical structure of QED, but through a mechanical or causal picture rooted in

[3] For discussion of the role of visualizability in the history of quantum physics, see [9]; [10, ch. 7].

[4] Sanchioni [8, p. 7] takes this generality to be a kind of depth, noting that "structural explanations in physics—those that appeal to symmetry, gauge invariance, or mathematical consistency—often carry greater explanatory depth than mechanical models precisely because they do not depend on contingent assumptions or idealizations." He goes on to write that the structural explanation of the anomalous magnetic moment of the electron in QED that he presents "is not a product of dynamical evolution in spacetime, but of the formal structure of the quantum field theory itself ... it is independent of the internal structure of the electron." Here Sanchioni might mean either that the electron is a point particle with no internal structure (taking a stance on ontology) or that the explanation can be applied without needing to fill in a particular internal structure of the electron (which makes it seem like there is such an internal structure that one could attempt to study).

> space and time. . . . explanation requires reference to dynamical mechanisms, preferably visualizable and spatially localizable."

Although partial explanations of particular phenomena can be given without referring to "dynamical mechanisms" and these explanations can be enlightening, full explanations should be given in terms of things that exist (the ontology), the dynamical laws governing the behavior of such things, and/or any other non-dynamical laws there may be.[5] You would generally expect an explicit proposal about the ontology to be visualizable, but the picture that is painted of reality need not be familiar. What matters is that the picture is precise.

Why would you give up on the goal of understanding what is actually happening and settle for an instrumentalist approach to a particular theory? There are two possible motivations: (1) the prospects seem dim for arriving at any clear picture of reality that could explain the empirical success of the theory, or (2) there are multiple incompatible pictures of reality that could explain the empirical success of the theory and the prospects seem dim for us ever being able to determine which is correct. Fuchs and Peres [17] articulate the first motivation when presenting an approach to quantum physics that is arguably instrumentalist:

> "We have learned something new when we can distill from the accumulated data a compact description of all that was seen and an indication of which further experiments will corroborate that description. This is what science is about. If, from such a description, we can *further* distill a model of a free-standing 'reality' independent of our interventions, then so much the better. Classical physics is the ultimate example of such a model. However, there is no logical necessity for a realistic worldview to always be obtainable. If the world is such that we can never identify a reality independent of our experimental activity, then we must be prepared for that, too."

Alternatively, one might be led to instrumentalism about quantum physics by the second motivation and the thought that we will never be able to settle—through either experiment or analysis—which particular explicit story about reality is correct: Bohmian mechanics, the many-worlds interpretation, a spontaneous collapse theory, or something else.[6] Those of us who actively debate these options tend to be more optimistic, considering many ways in which the list might be narrowed down.

I do not see an argument from Sanchioni [8] for either (1) or (2). Sanchioni correctly points out that standard explanations of the electron's anomalous magnetic moment in QED do not come with a particular explicit story about the electron's nature and behavior. Such explanations are "not reducible to mechanical narratives or visualizable causal processes" [8, p. 9]. Still, the existence of such explanations does not mean that

[5] See [16].

[6] For discussion of the merits of this second motivation for instrumentalism about quantum physics, see [18].

we cannot arrive at better explanations by introducing explicit proposals about the underlying ontology (or that we cannot ever settle which such proposal is best). We should try.

3 A Comparative Question

In [1], I analyze the electron's magnetic moment within a precursor to quantum field theory where the electron is described by a function ψ that evolves via the Dirac equation and the electromagnetic field is governed by Maxwell's equations (with the charge and current densities of the electron appearing as source terms). This Maxwell-Dirac theory can be interpreted either as a semiclassical theory in which ψ is the electron's quantum wave function (interacting with a classical electromagnetic field) or as a fully classical field theory in which ψ is the classical Dirac field. Each option comes with its own path to quantum field theory, as will be discussed in section 4. Sanchioni takes the first option, describing the precursor as a semiclassical theory.

In [1], I posed a comparative question about the relation between the precursor (Maxwell-Dirac) theory and quantum field theory:

> "How does the move from such a precursor to quantum field theory take you from a state-dependent magnetic moment to a fixed magnetic moment?" [1, p. 23]

In his article, Sanchioni [8, pp. 2, 10] aims to "challenge this framing" by offering an "epistemic inversion": "What Sebens presents as a puzzle for QED—how it 'nails down' a fixed magnetic moment—should instead be seen as a flaw of the semi-classical precursor." I do not follow why Sanchioni sees a tension here and uses the word "instead." The precursor theory is certainly flawed and one flaw, among many, is that it does not yield the correct (fixed) magnetic moment of the electron (instead predicting a state-dependent value). Another flaw, explored in [19], is that the Maxwell-Dirac theory includes a problematic self-repulsion force that would rapidly tear electrons apart.

Unlike Barut *et al.* [20–24] (whose approach is discussed in [1, sec. 5]), I do not view this kind of precursor theory as a competitor to QED. It is merely a stepping stone [8, p. 9]. Still, I think there is an important puzzle here about nailing down the electron's magnetic moment. The puzzle is not a puzzle within QED itself. As Sanchioni [8, sec. 2] and many textbooks explain, QED accurately predicts the (fixed) magnetic moment of the electron. The puzzle that I have posed is a comparative one, about the relation between two physical theories. I want to understand how the moves that take you from the precursor to QED end up fixing the magnetic moment of the electron (something that Sanchioni [8, sec. 2] begins to address, but does not fully resolve). I would like to see a calculation of the electron's magnetic moment in QED that more closely resembles the calculation within the precursor theory, so that we can track how the effects studied there are modified in QED.

Sanchioni [8, p. 9] presents two ideas as to what I might be up to in [1]:

> "On one reading, his semiclassical model is a heuristic device—a conceptual aid to visualize how self-interaction might yield corrections to g [(a way of specifying the electron's spin magnetic moment)]. On another, it is presented as a physically deeper, perhaps more 'realistic' account of the anomaly's origin."

Neither interpretation is correct. The first reading is too weak, as the goal is not merely to understand "how self-interaction might yield corrections to g," the goal is to work towards an understanding as to how self-interaction *actually does* yield corrections to g. Studying the precursor is a warm-up exercise towards better understanding what is going on in QED. It is true that the precursor's account is, in a sense, more "realistic" than the standard textbook QED story, but that virtue does not make the precursor a viable competitor to QED (because the precursor does not predict things like the anomalous magnetic moment correctly). I agree with Sanchioni [8, p. 9] when he says that "Sebens's semiclassical model does not provide an alternative explanation of the anomaly on par with quantum electrodynamics" and that it "illustrates the limitations of precursor theories." What I want to understand better is how those particular limitations are transcended in QED.

4 Working on Quantum Field Theory

In section 2, we saw that Sanchioni and I disagree about whether QED is fine as it is or "somehow incomplete." Here, let me elaborate on the incompleteness and how I think extant explanations of the electron's anomalous magnetic moment might be improved.

QED is incomplete on two levels. First, we have rejected the simple wave functions on configuration space from non-relativistic quantum mechanics and it is unclear what takes their place: particle wave functions that allow for particle creation and annihilation, or field wave functionals. I examine this debate between particle and field approaches to quantum field theory in [7], noting that work remains to be done to make either approach viable.[7] Second, there is the question of which way of solving the quantum measurement problem should be applied to quantum field theory: Bohmian mechanics, many-worlds, a collapse theory, or something else. To precisely articulate the laws and ontology of QED, we need to resolve the issues at both levels in a coherent package. For our purposes here, let me focus on the first level and the debate between particle and field approaches to QED.

Sanchioni does not explicitly discuss particle and field approaches to quantum field theory, and does not seem to be concerned about the debate between them. He writes: "this is precisely the explanatory power of QED: to go beyond wavefunctions and fields

[7] See also [25, ch. 11]; [26, sec. 6.5].

as ontological entities, and instead to encode physical properties in the structure of interaction and symmetry, formalized through operator algebras and Green's functions." Are we going "beyond" wave functions and fields by replacing them with something more sophisticated (like wave functionals) or by discarding any representation of the physical state at all? If it is the former, then it seems urgent to settle the question of whether we should take a particle or field approach to QED (or some other approach). If it is the latter and there is no representation of the state at all, then we are taking an instrumentalist approach to QED and, as was discussed in section 2, I do not think we should give up so easily on the project of understanding what is happening in nature.

A proponent of the particle approach to quantum field theory might view the Maxwell-Dirac precursor theory (from section 3) as a semiclassical theory, describing a single quantum particle interacting with a classical electromagnetic field. You could then move to QED by allowing for superpositions of different numbers of electrons and positrons (at different locations) and somehow replacing the classical electromagnetic field with photons.

I prefer the field approach to quantum field theory for a variety of reasons (presented in [7]). Thus, I think that quantum states should be represented as field wave functionals that describe superpositions of classical field configurations. Taking this approach, one can think of the models of the electron within the Maxwell-Dirac precursor theory as describing two interacting classical fields (the Dirac and electromagnetic fields). Studying these models is a way of studying the electron states that are superposed in QED, examining a classical field theory to better understand the quantum field theory that it becomes upon field quantization.

Criticizing my attempts to study the internal structure of the electron, Sanchioni [8, p. 6] writes that "the extended electron approach seems to sacrifice the structural insights of QED for a mechanical picture that is not derivable from the full quantum theory." I would like to be clear that what we are building up to here is a version of the "full quantum theory" (in this case, QED) that treats electrons as extended, which is arrived at not by radically overhauling QED, but instead by carefully formulating it as a theory of wave functional evolution.

Let me clarify one last thing. In [1, p. 3], I list four reasons to be dissatisfied with standard derivations of the electron's anomalous magnetic moment within quantum field theory. Briefly, they are (1) the appeal to an external electromagnetic field, (2) the use of diagrams depicting time evolution to arrive at a property of the electron at a moment, (3) the treatment of the electron as a point particle, and (4) the lack of a clear physical picture to explain why the electron acquires an additional anomalous magnetic moment. In [1, p. 26], I explain how the four shortcomings can be addressed when studying the electron's magnetic moment within the Maxwell-Dirac precursor theory and suggest that we may be able to use these insights to arrive at an improved explanation of the electron's anomalous magnetic moment within quantum field theory. As I put it [1, p. 26]: "These four improvements could potentially be carried over into quantum field theory, but to do so we must work to understand how calculations of the anomalous magnetic moment that can be performed within quantum field theory relate to the calculations that can be done in the context of the Dirac equation." Sanchioni [8, pp. 6–7] points out that any improvements the precursor theory may make on (1)–(4) are not worth the "epistemological cost" because, among other things, "the anomaly is no longer universal, but dependent on arbitrary modeling choices." He is of course correct, as I emphasized in section 3, that the precursor theory is not superior to QED. Still, I believe that there are lessons to be learned from it as we seek to better understand QED and how it might explain the electron's anomalous magnetic moment. In QED, we may be able to achieve improvements on these four fronts without bearing any cost.

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