Pauli's Idea of the Neutrino: how Models in Physics allow to revive old Ideas for new Purposes.

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Abstract. Models have proven themselves to be the key catalyst of many new ideas in science. However, it is not yet fully clarified why models can fulfill such an important heuristic role. The two main reasons stated in the literature – the mental simulation of various scenarios and the wide cross-fertilization across various disciplines – seem to leave out one of the most obvious features of models: they are designed for a purpose. Therefore I investigated why, while the construction of models is a goal-oriented task with a predefined purpose, the use of models yields so many new ideas in science. This paper presents my conceptual analysis together with a detailed historical case study.

The functional design of models forces scientists to explore vigorously older ideas to adapt them: as the lacunas in a functional model are also functional, scientists need to modify older ideas (that were formulated for different purposes) to fit the present functional gaps in their models. As such, they construct new ideas. The detailed historical case study exemplifies this by showing how Pauli's original suggestion of the neutrino was, in fact, such an adaptation of Rutherford's earlier idea of the neutron. The present analysis and case study suggest that functional adaptations are salient but often overlooked features of model based investigation.

1 Introduction

Models perform an important heuristic role in scientific investigation (Redhead 1980, Morgan and Morrison 1999). Their success in this role is typically explained by two widespread practices. On the one hand, because of their dynamic nature, models allow to explore extensively and to experiment mentally with existing theories. As such, one can simulate various scenarios, and identify and mediate lacunas and anomalies in a given theory (Morgan and Morrison 1999, p. 19; Nersessian 2008, p. 185). On the other hand, models can be extremely fruitful. Many simple abstract models have been applied to a variety of contexts outside their original field, a process that has led to a huge interdisciplinary cross-pollination.[1] This shows that scientists are actively looking for useful models that can be applied to problems in their own field.

In this paper, I want to add a third important heuristic practice involving models. Models have a typical functional structure or, to put it in other words, they are designed with a purpose in mind. This means that lacunas or gaps in a model are by definition also functional, which invites the designer to actively explore old ideas that might serve to fill these gaps.

The aim of this paper is to explicate and illustrate this third practice and its relation to the other two by presenting a case study of a famous idea in the history of modern physics, i.e. Pauli's original suggestion in 1930 of the particle that was named the *neutrino* afterwards. In Gauderis 2013, I have argued that this idea was not so original as Pauli might have thought it to be, but can be seen as an adaptation of Rutherford's original idea of the *neutron* in 1920. In this paper, I will further substantiate this claim by explicating both the problems that Rutherford and Pauli were working on, as well as the models they employed for their purposes. This analysis will interpret this history as an example of how an idea that arose in a certain program managed to stay alive, even though the program grew obsolete, in order to be picked up ten years later as the missing piece in a model for another and much more prominent puzzle in the field.

In the next section, I will start by expanding on the role of models in scientific discovery, and show how the three heuristic practices identified above can be understood in generic terms, although the scope of this analysis will be restricted to the heuristic use of models in physics. The main objective of this section is to provide us with a conceptual framework to analyze the case study, which naturally falls apart into two distinct parts: Rutherford's reasoning and models in 1920 and Pauli's reasoning in 1930, each of them being discussed in a separate section.

2 Models and Scientific Discovery in Physics

As some scholars have noticed, it is very hard to give a precise definition of a model, even if we restrict ourselves to models in physics (Hartmann 1995, p. 52; Nersessian 2008, p. 12). Such a definition is, however, not necessary and one can content oneself, as Nersessian proposes, with a loose definition that is sufficient to capture the way physicists think of models.[2]

From the most general point of view, a model can be conceived as an abstract imaginary system of interrelated parts that has as a whole certain distinguishing characteristics. The most important characteristics of models are (1) their functional design,

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[1] There are numerous examples of this cross-fertilization. Some of the more spectacular examples are the so-called genetic algorithms in Artificial Intelligence, which are based on natural evolution models (e.g. Goldberg 1989), the use of Markov chain-models to identify authors in philological studies (e.g. Khmelev 2000) and the use of phase transition models from physics for problems in social philosophy of science (e.g. De Langhe 2012).

[2] By purely focusing on the epistemological role of models, we evade at the same time the discussion about the ontology of models. For an introduction to the latter discussion, see Frigg and Hartmann 2012.

(2) their representational potential and (3) their susceptibility to manipulation, all of which are uncontested in the relevant literature. Models in science are in the first place functional, or as Morrison and Morgan state it, they are designed or constructed to “function as tools or instruments” (1999, p. 11). The purpose of this design can be a variety of scientific activities such as theory construction, explanation, prediction, suggesting which data should be collected, etc.[3] The main reason why models can function as a tool for all these purposes is their second property: they are meant to represent certain features of the world, or as Nersessian explains it, “they are designed to be structural, functional or behavioral analogues of their target phenomena” (2008, p. 12). Finally, the reason why models can be considered as tools is their susceptibility to manipulation, and as such they distinguish themselves from mere representative descriptions. The design of a model is such that one can interact mentally with the model by manipulating certain features, adjusting certain parameters or adding or removing certain parts, all of which represent interventions in the target field (Morrison and Morgan 1999, p. 12).[4]

With this characterization in mind, we can explain how models play their role in the three heuristic activities identified in the introduction. When a scientist is confronted with a new target phenomenon, i.e. a collection of experimental data, she can try to structure this data by constructing a model. She does not have to start this activity from scratch. Generally, some initial constraints are available from a general theory or some related models. For example, if a researcher tries to construct a model for a particular type of nuclear reactions, initial constraints are raised by her model of nuclear constitution and some general theories such as quantum mechanics. Still, it is obvious that there are no clear algorithms at this stage, but that this is more a matter of skill. In the literature, this activity has been described as constructing with bits from different sources (Morgan and Morrisson 1999, p. 15-16), as matching representations to mathematical structures (Czarnocka 1995, p. 30) or as constructing a hybrid between target and source domain (Nersessian 2008, p. 28). The common denominator is that this activity is a bit-piece assembly process. This assumes that scientists have certain simple blueprints at hand, simple mathematical models and structures that they have acquired over the years, and which they can be combine with theory, experimental data and various representations. The so-called model constructing skills consist then in maintaining and expanding such a set of blueprints, and the application

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3 S. Epstein (2008) distinguished seventeen different reasons why one should model. Apart from the most straightforward reasons prediction and explanation, he identifies models also as a key method to e.g. finding gaps in your data or formulating new research questions. While models are often constructed for several of these reasons, he convincingly argues that e.g. models for prediction and explanation are typically of a different nature. Not all of his seventeen reasons, however, should be considered as purposes for the design of a particular model. His paper aims mostly to convince scientists in fields where models are less common, and some of his reasons such as “teaching us a scientific outlook” are just interesting qualities that result from the regular use of models.

4 Because of this feature, the use of models has received a central place in the interventionist view of science going back to Hacking and Cartwright (Cartwright et al., 1995).

of this set to various problems is exactly the second heuristic practice that I have identified.

Second, the models' susceptibility for manipulation allows us to simulate and explore within the constraints that are imposed on the model by both its internal (formal) coherency and the knowledge of the target domain. This hybrid construction gives the models a relative autonomy, which allow them to identify lacunas and anomalies in both the theory and the model itself, the first heuristic practice stated above.

Now we can specify the third practice that makes models such a useful heuristic tool. The functional design of a model ensures that every part of the model has its own function. As such, if a lacuna is identified in a model, this is a functional lacuna, i.e. the model misses something that can fulfill a function needed by the rest of the model. Researchers can try to come up with own and original ideas to fill these gaps, but, as the case study exemplifies, it is also very common that a researcher browses her own field for ideas that have the necessary properties. This is a different activity than the use of various models from other fields. Where in the latter activity the abstract structure of the model is borrowed and completed by adjusting the representational elements to objects in the field the researcher is working in, the researcher actively pursues in the former activity ideas from her own field that were proposed for different purposes or problems, some of which might have already become obsolete.

To sum up, I have identified three scientific heuristic practices involving models, which explain why the use of model is heuristically so successful. First, models allow by their partly formal nature to be applied to many problems that can be situated in other fields, or shed at least some initial light on these problems. Second, they allow for dynamic simulation on the basis of which researchers can explore the various combinations of the model's parameters. Third, because of their functional design they invite scientists to actively reconsider old ideas in order to spot an idea that has the right characteristics to fulfill a particular function in the grand design of the model.

In order to apply these concepts to the case study, I will first expand on the two types of models that will be discussed in the case study, i.e. constitution models and reaction/process models. *Constitution models* are the oldest type of physical models and relate to ancient philosophical questions about the nature of things. The main purposes of these models are explanatory: by specifying the various parts and the total structure of the target phenomenon, one aims to explain certain properties of the whole, such as its stability or fluidity. As *process* and *reaction models* started to emerge only since the scientific revolution, they are much younger types of models. Their main purpose was not so much to explain the nature of the represented changes, but rather to explicate the necessary conditions and the results to be expected. Experimentalists used them as a guide line to manipulate and control physical reality. In other words, these types of models are designed for prediction and not for explanation. The scientific revolution and these experimental models put at the same time more stringent conditions on the older constitution models: they had to become compatible with (most of) the process and reaction models of the target phenomenon and their descriptions had to be limited to qualities that are in principle testable. Therefore, constitution models in physics are generally limited to describing the various subentities and specifying the forces or mechanistic properties that keep them together. Still, their main purpose remains explanatory as they are not strictly needed for prediction.

Both types of models are – as all models are – dynamic by nature and allow the scientist to interact with their various parts. For constitution models, these dynamics lie mostly in the possibility to explore what combinations of subentities can possibly exist. To discuss the dynamics, I need to distinguish between process and reaction models. I view reaction models as models that take the represented change to occur instantaneously, e.g. models for radioactive decay or chemical reactions. In contrast with process models, which represent a gradual or stage-based change of the target phenomenon, reaction models represent only the situation before and afterwards, considering the change as something that has happened at a certain time in between. The main goal of these models is to specify, apart from the conditions under which the reaction can take place, which characteristics and entities are conserved and how the non-conserved properties change. Their main dynamics lies in the fact that one can mentally explore various situations to picture what the result of the reaction would be. Process models, which do not occur in the case study, draw the attention more to the change of the target phenomenon itself, and enable scientists to simulate various scenarios how they might control or accommodate the process.

By ascribing different purposes to these different types of models, while still assuming their compatibility, I take models to be more or less autonomous but related to each other. The autonomy of the models' purposes is also one of the reasons why Morgan and Morrison (1999) consider models to be independent from physical theories. The other reason is that models are also constructed more or less autonomously from theory or as Cartwright (1999) states it: "Theories do not provide us with algorithms for the construction of models, they are not vending machines into which one can insert a problem and a model pops out". This relative autonomy will also help us to understand the role of theories such as quantum mechanics and classical electrodynamics in the case study. The semantic view (in which theories are superfluous families of models) and syntactic view (in which the logically structured theory carries all scientific value) are both too restricted to capture how theories and models function in the endeavors of scientists.[5] Cartwright (1983) has described the laws in a theory as "schemata that need to be concretized and filled in with the details of a specific situation, which is a task that is accomplished by a model", and such initially under schemata constructed models can develop their own dynamics, which might lead to the suggestion to withdraw a certain aspect of the theory (see e.g. Bohr's suggestion to withdraw the energy conservation theorem (Gauderis 2013)).

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5 See Frigg and Hartmann (2012) for an excellent summary of these two points of view.

3 Introduction to the Case Study

The case study in this article is Pauli's original suggestion of a particle that was called the neutrino by Fermi in 1933. In Gauderis 2013, in which I discussed the various proposed hypotheses to solve the anomalous β-spectrum in the late 1920s, I have argued that Pauli's idea of the neutrino was basically an adaptation of the old idea of the neutron suggested by Rutherford in 1920. In this article I take on the challenge to explicate how this adaptation should be understood in terms of the characteristics of models. The case study naturally falls apart in two parts. I will first take the time to explain Rutherford's project around 1920 and show how the idea of the neutron emerged from his model. Next, I will present the other case, which was the completely different puzzle of the curious β-spectrum. I will restrict myself however to Pauli's suggestion, and show how the model he had in mind led him to think that the neutron might be the solution.

4 Rutherford's Idea of the Neutron

Rutherford suggested the idea of the neutron for the first time in his Bakerian lecture (1920). The main reason why he believed this idea to be valuable was because he thought that its existence "seems almost necessary to explain the building up of the nuclei of heavy elements" (p. 397). Translated to our conceptual framework, Rutherford perceived an incompatibility between his constitution model of atomic nuclei and the theory of classical electromagnetism, because the laws of the latter do not allow the building up of the more heavy nuclei. This had led him to investigate further the constitution of nuclei, partly by real-life experiment, partly by mental simulation of the model and logical thinking. It was exactly this simulation of various possibilities that convinced him that there might possibly exist a neutron, although his perception of it was totally different than our current understanding. The fact that this idea, yielded by simulation of the model, could fill the functional gap in the model convinced him of the soundness of this idea, a conviction that inspired him to look tenaciously for experimental proof over the next ten years. Finally, in 1932, his close collaborator Chadwick managed to assemble sufficient evidence to confirm its official discovery.

Let us first explain Rutherford's nuclear model. Like many of his contemporaries, he believed that the nucleus consisted out of "electrons and positively charged bodies" such as helium and hydrogen nuclei (p. 377). But, as he had already suggested in 1914, all these positively charged bodies can ultimately be considered as a combination of positively charged hydrogen or H-nuclei (which became gradually called *positive electrons* or *protons*) and negatively charged *electrons*,[6] kept together by the elec-

[6] Hanson (1963, p. 157-59) explains the fact that for a long time scientists refused to consider any other elementary particle besides protons and electrons by pointing to the fact that these two particles were at the same time considered to be the elementary subunits of the two types of electrical charge. As there was no other type of electricity, there was no reason to presuppose another elementary particle.

tromagnetic force[7] (Pais 1986, p. 230; Rutherford 1920, p. 395). For example, the He-nucleus or *α-particle* was considered to be a very stable combination of four H-nuclei and two electrons. This so-called *proton-electron* or *p-e model* explained convincingly the atomic mass and charge of the various elements. A nucleus with atomic mass *A* and charge *Z* consisted of *A* protons (which all have, as they are hydrogen nuclei, elementary mass, and, hence, add up to the atomic mass *A*) and *A-Z* electrons (which made sure that the total charge of the nucleus was positive *Z*). The Coulomb force between these positive and negative particles caused the nucleus' stability.[8]

Given the common ontology of these days, this was the only viable model available. Still, this model had several difficulties.[9] As Rutherford mentions, the apparent lack of magnetic moment of the intranuclear electrons hints that these electrons must be somewhat "deformed" (p. 378) and that they are in no sense comparable to the extranuclear electrons orbiting around the nucleus. But his main problem was the constitution of large nuclei. As soon as a nucleus contained a certain amount of protons, the combined repelling Coulomb force of these would be just too large to ever let another proton come close enough to swallow it. The reason why he was so vividly aware of this problem, was because he observed it on a daily basis in his experiments. While he found it possible to shoot lighter elements with α-particles or He-nuclei, and initiate a collision, he found it impossible to penetrate larger nuclei due to their high electrostatic repulsive forces.[10] This also nicely illustrates that Rutherford perceived experimental data, models and theories all as more or less autonomous entities that should be made compatible with each other.

Rutherford thought he could cope with these problems by assuming certain substructures in the nucleus. Nuclei were not just a heap of protons and electrons that attract all of each other more or less equally. He thought that protons and electrons bound in small stable substructures, which in turn grouped together to form the full nucleus. The reason why he (and the physics community in general) had this idea was the remarkable stability of the α-particle. In experiments it turned out to be impossible to break up this element by collisions (1920, p. 379). It was also observed as an independent structure in α-decay, which led several people to assume that it was as such part of the nucleus. Around 1920, it was Rutherford's main experimental program to find more stable combinations like this to complete the nuclear constitution model.

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7 The only two forces known at the time were gravity and electromagnetism, but, because gravity is too weak to play a role at such a small scale, the only viable option was electromagnetism.

8 Notice the contrast with our present day views, in which we take a nucleus to consist of *Z* protons (accounting for the nuclear charge) and *A-Z* neutrons (adding the total mass up to *A*), kept together by the residual strong force. For example, it is now thought that the He-nucleus consists of 2 protons and 2 neutrons instead of 4 protons and 2 electrons.

9 At this point, I only mention problems that were already known in 1920. The more famous problems for this *p*-e model, such as the wrong statistics of the nitrogen nucleus and the Klein paradox, arose only during the 1920s.

10 It was exactly because part of the α-particles were repelled from the gold foil in the famous Rutherford-Mardsen-Geiger experiments that Rutherford inferred the existence of the nucleus in the first place.

Because he was not able to reach the nucleus of heavier elements with α-particles, he conducted mainly experiments on lighter elements (nitrogen, oxygen, carbon) in order to produce collisions and study the remaining parts. His first discovery were H-nuclei or protons. This was important because, although it was generally assumed that protons existed independently in the nucleus, it was "the first time that evidence has been obtained that hydrogen is one of the components of the nitrogen nucleus." (p. 385), and that, hence, the *p-e* model had some experimental ground. Second, he discovered a certain atom, which he called X, with atomic mass 3 and nuclear charge 2, which made it "reasonable to suppose that atoms of mass 3 are constituents of the structure of the nuclei of the atoms of both oxygen and nitrogen." (p. 391)

In order to figure out the substructure of this atom X, he reasoned that "from the analogy with the He-nucleus, we may expect the nucleus of the new atom to consist of three H-nuclei and one electron." (p. 396), which made this atom a snug fit in the *p-e* model. But when he realized that this means that a single intranuclear electron can bind three protons,[11] it appeared to him "very likely that one electron can also bind two H-nuclei and possibly also one H-nucleus" (p. 396). In other words, by mentally exploring what is also reasonable to expect according to the *p-e* model, he came to the idea of a close binding of one proton and one electron, an "atom of mass 1 and zero nucleus charge". He expected this combination, which he started to call the neutron later, to be a very stable entity with "very novel properties". Because there would hardly be any electromagnetic field associated with this neutral combination, it would be able to travel rather freely through matter. Therefore, it might reach the nucleus of heavy atoms without suffering from a repelling force, where "it may either unite with the nucleus or be disintegrated by its intense field" (p. 396).

The thought process of how Rutherford came to the idea of the neutron is highly intriguing, because hardly any part of it is still acceptable according to our present standards: the *p-e* model is plainly wrong; later experiments did not confirm the existence of the X-atom; the whole idea that there exist certain substructures in the nucleus is flawed; the constitution of heavy nuclei poses no problems; and above all, according to our present understanding, it is absolutely untrue to consider a neutron as a combination of a proton and an electron.[12] Still, judged in light of Rutherford's background knowledge, his thought process is a very sane and sound piece of reasoning in which he improved his constitution model by combining experimental data with mental simulation of his model. And, although Pais claims that this whole search program for atomic substructure has left no mark on physics (1986, p. 231), I have shown that this program has led to a valuable idea, which is not only the forerunner of our current neutron, but also, as I will show in the next section, of our current neutrino.

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[11] A single intranuclear electron was not yet observed beforehand, hydrogen had according to the *p-e* model no intranuclear electrons, while the next element in the periodic table, helium, had already two.

[12] The idea that neutrons were not close combinations of protons and electrons took some time to settle. When Heisenberg published in 1932 the first elaborate proton-neutron model of the nucleus, he left the question still open.

5 Pauli's Idea of the Neutrino

Pauli's suggestion was an attempt to answer a very complex experimental puzzle, which had been intriguing the physics community for several years. In 1927, Ellis and Wooster had published an experiment that convincingly showed that the electrons in radioactive β-decay were emitted with a broad and continuous range of energies. This puzzling fact did not only break the analogy with α-decay, in which the energy of the emitted α-particles was determined for each possible α-decay, it also triggered some very counterintuitive hypotheses. For example, Rutherford and Chadwick suggested that not all nuclei of a particular β-unstable element were identical, because they had different internal energies, and Bohr suggested that energy is not conserved in β-decay such that the electrons can escape with a wide range of different energies.[13] At the time, this puzzle was not the only problem for nuclear research. The experiments performed in 1926 that showed that nitrogen nuclei behaved according to Bose-Einstein statistics, proved another serious anomaly for nuclear theory and the *p-e* model. According to latter, nitrogen (with atomic mass 14 and nuclear charge 7) consisted out of 14 protons and 7 electrons, and should, hence, have a half-integer total spin, because both protons and electrons have spin ½. This means that, according to the *p-e* model, nitrogen nuclei should behave according to Fermi-Dirac statistics. The observed Bose-Einstein statistics, however, required that the nucleus consisted of an even number of half-integer particles, adding up to an integer total, which is required to explain these statistics.

Pauli was introduced to these problems in 1929 by Bohr, who was thinking about a restriction of the principle of energy conservation to solve these issues, an idea that gave Pauli "very little satisfaction" (according to a letter to Bohr reprinted in Peierls 1986, p. 5). As Bohr and his collaborators continued this path of energy non-conservation, Pauli started, apart from continuously criticizing them, thinking about another idea, which he formulated for the first time in December 1930. Let us first, as we did with Rutherford, try to understand Pauli's view on and models of the matter. We can then explain how he adapted Rutherford's idea for his own purposes.

Like all of his contemporaries, Pauli saw radioactive decay in terms of a reaction model in which an unstable nucleus (the situation before) decayed spontaneously into a remnant nucleus and the observed emitted α- or β-particle plus some γ-radiation (the situation afterwards). For α-particles, the model of this reaction preserves both energy and electric charge, but for β-decay, the unexplainable continuity of energies in the situation afterwards had led some to suppose that this continuity already existed in the situation beforehand (Rutherford and Chadwick), or to suggest to retract the energy conservation constraint for this model (Bohr). It was this final suggestion that triggered Pauli to address this problem. To understand why he was so opposed to Bohr's ideas, we have to look at some of his criticisms. In a letter to Klein, a close collaborator of Bohr, he challenges Bohr's suggestion to retain charge conservation but abandon energy conservation in β-decay by the following thought experiment:

[13] For an extensive exploration of this puzzle and all suggested hypotheses, see Gauderis 2013.

> "Imagine a closed box in which there is radioactive β-decay.[...] If the energy law thus would not be valid for β-decay, the total weight of of the closed box would consequently change. This is in utter opposition to my sense of physics! For then it has to be assumed that even the the gravitational field – which is itself generated [...] by the entire box (including the radioactive content) – might change, whereas the electrostatic field, [...], should remain unchanged because of the conservation of charge." (reprinted in Jensen 2000, p. 153)

The heart of Pauli's criticism is that the field formalisms for gravity and electrostatics, both depending on inverse-square laws, are constructed analogously and, hence, considered to be of the same kind. By breaking this analogy, Bohr's suggestion has the far reaching consequence of undermining the physical concept of a field. Unlike most quantum theoreticians who had hardly ever to deal with gravity,[14] Pauli was also an expert in the field of general relativity.[15] Because of this, Pauli was much more aware of field structures as the main ontological concepts for physical reality than nuclear physicists in general. This explains why Bohr's ideas were so disturbing for him.

If Pauli was convinced that the conservation laws must hold in this reaction model, it probably occurred quite fast to him that the only way to balance the disequilibrium between the before and after situation was by adding something to the picture. But nothing else was observed so far in the β-decay experiments. Hence, he needed to look for something that was unobservable or at least very hard to observe. As conservation of electrical charge already applied, it had to be also electrically neutral. In other words, his reaction model for the process of β-decay had suddenly a gap, which should be filled by an idea or entity which had these two properties. In an autobiographical article, he wrote the following:

> "Then I have tried to connect the problem of the spin and statistics of the nucleus with the other problem of the continuous β-spectrum without giving up the energy conservation principle through the idea of a neutral particle. I have sent a letter about this [...] in December 1930, when the heavy neutron was not yet experimentally found." (1957, p. 1316, my translation)

In this letter[16] he presented a "desperate remedy" to solve these two problems, namely "that there could exist electrically neutral particles in the nucleus, which I want to call neutrons" (1957, p. 1316, my translation). In Gauderis 2013, I have argued that this idea was largely an adaptation of Rutherford's idea. The main arguments for this thesis are, first of all, the fact that Pauli used the term "neutron" for this nuclear constituent, while the term "neutron" was still actively used by Rutherford and his collaborators in articles, a fact Pauli must have been aware of. Second, the fact that he points out why Rutherford had no success in finding his neutron before

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14 The effects of gravity are far too weak to be noticeable at the atomic scale.

15 At the age of 21, he wrote a summarizing monograph on the general theory of relativity, which impressed even Einstein (Pais 2000, p. 215).

16 The original German text of this letter can be found in Pauli 1957 (p. 1316). An integral translation can be found in Brown 1978 (p. 27).

1930 right before presenting his own idea hints that he thought to have found what Rutherford was looking for. Finally, he seems to have abandoned the idea that his particle was a nuclear constituent only around 1932, the year in which the "heavy" neutron was discovered by Chadwick.

The functional gap in Pauli's model was clear: he needed something that could carry some spin and energy, had zero charge and was very hard to detect. At the same time, there was an old and well-known hypothesis of a neutral particle that is hard to detect. Although it had been suggested in a completely different context and was aimed at another purpose, its properties made it suddenly a viable candidate to fulfill the functional gap of another problem. As such, Pauli employed this idea in his model, calculated its further properties such as its spin and possible mass, and was able to put forward the first version of his attempt to solve the β-puzzle.

6 Aftermath of the Case Study

In 1932 Chadwick, a close collaborator of Rutherford at the Cavendish laboratory, announced the experimental discovery of the neutron. In his article (1932) he stated explicitly that what he found was the particle Rutherford envisioned in his Bakerian Lecture in 1920. This discovery was directly accepted by the physics community, and gave rise to the first proton-neutron models of the nucleus later that year, which were able to explain the anomalous statistics of nitrogen nuclei. Pauli's hypothesized particle, which had, in contrast with the discovered "neutron", a very low mass, was dubbed the "neutrino" by Fermi in 1933 to distinguish it from Chadwick's discovery. Gradually, this solution for the anomalous β-spectrum drew more adherents until it was incorporated in Fermi's model for β-decay in 1934, after which consensus followed shortly after. Bohr himself admitted defeat in 1936. However, it took until 1956 before experimental evidence was found for the neutrino.

7 Conclusion

In explaining the success of using models for heuristic purposes, the functional design of models is often left out of the picture. In this paper, I showed by means of a conceptual analysis and a detailed historical case that precisely this functional design of models forces researchers to explore vigorously old ideas in order to adapt them for their current purposes. As such I identified a third practice – besides the often mentioned mental simulation of various scenarios and wide cross-fertilization between different fields – that explains the heuristic success of models.

Old ideas are often reused, generally adapted or employed as an analogy or metaphor. The case study in this paper explains in detail how Pauli filled the functional gap in his model for radioactive β-decay by adapting an old idea that figured in Rutherford's atomic constitution model. But not only entities or objects serve as ideas that can be adapted for new purposes; this is illustrated by Bohr's suggestion to retract the energy conservation principle. At least twice before did he use this same idea to solve a certain puzzle, each time with a completely different purpose.[17]

Although it is for many cases impossible without a detailed case study to tell whether it concerns the use of an old idea or whether one came independently to the same idea, there is certainly no reason to suspect that all these ideas were original. As such, if we want to understand how scientists use models and reuse them, it is important to be aware of how models invite scientists by their functional structure to actively explore old ideas in order to adapt them for their own purposes. Further case studies and formal analyses are, however, needed to understand the impact of this fact on our current methodologies.

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[17] See Gauderis 2013 for an overview of these earlier attempts.

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