Virtual Processes and Quantum Tunnelling as Fictions

1. INTRODUCTION

In a typically terse and insightful little paper from 1970, Mario Bunge examined the notion of virtual processes, defined as processes that do not conserve energy but last too short a time to be observable, and concluded that they "are fictions and as such have no rightful place in a physical theory" (Bunge 1970, 508). In this paper I am going to defend this conclusion by explaining the sense in which I think virtual processes are indeed fictitious, and how this supports Bunge's claim that they should be rejected as unphysical.

Of course, there are many ways in which an entity or process may be said to be fictional. If a fiction is any thing or process whose properties are in conflict with physical reality, then, as Hans Vaihinger observed in *Die Philosophie des Als Ob* (Vaihinger 1911), fictions are ubiquitous in science. There are idealizations such as Galileo's frictionless planes, models such as Faraday's mechanical model of the luminiferous ether or Bohr's "solar system" model of the hydrogen atom, calculation devices such as Ptolemy's deferents, equants and epicycles or renormalization in quantum electrodynamics, and now-abandoned theoretical entities such as phlogiston or the incompressible fluid of Maxwell's ether theory.[1] Indeed, some recent philosophers of science, like Nancy Cartwight, have claimed that all non-phenomenological scientific laws are about idealized models that are known not to be literally true of the world, and which would therefore qualify as fictions in Vaihinger's sense.[2] If all general scientific laws concern fictions, then fictions cannot be eliminated from science, as it seems Vaihinger himself proposed they should.[3] But philosophers sympathetic to scientific

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[1] There are, however, some salient differences in status among all the items that Vaihinger and others have classified as fictions. See in particular the excellent analysis of Margaret Morrison (2009, 110-135), who carefully distinguishes fictional models from idealizations and mathematical abstractions, even though all can yield concrete knowledge about the physical world while depending on highly unrealistic assumptions. I fully endorse her conclusion that the way in which any given fictional model does this depends on the specific structure of the model itself: "there is no general method that captures how fictional models function or transmit knowledge in scientific contexts" (133).

[2] Thus both Bas van Fraassen (1980, 35-36) and Arthur Fine (1993) have appealed to Vaihinger's arguments about the ubiquity of fictions in science to support their arguments against scientific realism. I cannot get drawn into that debate here, and refer the reader to (Suárez 2009) for discussion. My own views align with those of Paul Teller (2009) and especially Ron Giere, who criticises Fine's use of fictionalism in support of his case against realism (Giere 2009, 255-256).

[3] For discussions of Vaihinger's fictionalism, see Fine 1993, both of Suárez's contributions to Suárez (ed.) 2009, and Bokulich 2009, esp. pp. 92-93. See also the papers in Frigg and Hunter (eds.) 2010.

realism have also urged that models and fictional elements, far from being eliminable, are essential to the successful conduct of science. Thus even if one accepts Bunge's claim that virtual processes are fictions, further argument is required for his claim that they should be eliminated from physics.

Here I am going to avail myself of a very useful distinction made by Alisa Bokulich. She distinguishes between fictions that "give some genuine insight into the way the world is and do seem to have some genuine explanatory power", which she calls *explanatory fictions*, and those that do not, even though they "justify themselves by their utility and expediency", called by her *mere fictions* (Bokulich 2009, 103). As an instance of the first kind of fiction she cites an example given by two physicists, that of light rays: "When one sees the sharp shadows of buildings in a city," say Kleppner and Delos, "it seems difficult to insist that light rays are merely calculational tools that provide approximations to the full solution of the wave equation" (Kleppner and Delos 2001, 610). They give this example in support of their appeal to fictional classical orbital trajectories for electrons in explaining quantum spectra, a case to which I shall return below. Other examples of explanatory fictions might be Bohr's model of the atom, or Maxwell's mechanical model of the ether: neither was intended as a wholly literal description of reality, but both successfully explained features of it.[4] By contrast, an example of a "mere fiction" would be Ptolemy's epicycles (in a contemporary use): "Although Ptolemaic astronomy might be a useful calculational tool for some navigators and surveyors, no one thinks that these fictions are giving any real insight into the way the world is or offering any explanations" (Bokulich 2009, 103). I shall be arguing that virtual processes should be understood as fictions in this "mere fiction" sense: not only are they not intended as a literal description of reality, they do not explain features of reality. They *purport* to give such an explanation, as does, for instance, the virtual process model for fundamental forces, where the force (electromagnetic, strong, etc.) is explained in terms of the exchange of a virtual boson (photon, pion, etc.). But unlike Bokulich's explanatory fictions, which are structural analogues that model aspects of reality by constraining the kinds of behaviour that are admissible in the theory, the

[4] See the penetrating analysis of Maxwell's mechanical model for the electromagnetic ether in Morrison 2009. Campbell's description of the electron trajectories in Bohr's model as fictitious, and Bohr's reaction, are discussed by Bokulich (2009, 95-97).

virtual process model explains forces solely in terms of processes that are strictly incompatible with that same theory. The "explanation" is therefore spurious.

My argument proceeds by a comparison with the phenomenon of quantum tunnelling, in which a particle is said to tunnel through a potential barrier that it does not have sufficient kinetic energy to surmount. This way of describing or understanding the process, I shall maintain, is also a mere fiction. The *phenomenon* that tunnelling purports to explain, on the other hand, is robust and extremely well-confirmed. It may not be a part of our first-hand experience, but it plays a central role in the theory of modern electronics, where the effect is exploited by all our amplifiers, cell phones, car engine computers and a vast range of similar devices on which we depend, as well as underlying the radioactive decay of alpha particles, nuclear fusion, and many other quantum phenomena. The effect is well understood, and is a consequence of the probabilistic nature of the quantum theoretical state function.

There is a sense, moreover, in which the phenomena explained in terms of virtual particles may also be regarded as instances of this tunnelling effect. As I shall explain further below, the strong nuclear force may be conceived in terms of a potential barrier separating two nucleons being penetrated by a virtual pion which effects a change of momentum equivalent to an attraction between the two nucleons. Similarly, such well-accepted effects as the Hawking radiation of black holes is explained in terms of the creation of virtual particle pairs at the Schwarzschild radius, one of which is reabsorbed into the black hole, the other escaping. In each of these cases there is an established effect. But, I shall argue, we can account for alpha decay, the Hawking radiation, etc. without positing particles that tunnel through potential barriers or virtual particles being created and absorbed. Although the phenomena usually explained in terms of them are real enough, particles tunnelling through potential barriers and virtual processes are mere fictions that do not help explain features of reality.

My argument is based on the cogent analysis of quantum tunnelling presented by Jean-Marc Lévy-Leblond and Françoise Balibar in their elementary quantum theory textbook, *Quantics: Rudiments of Quantum Physics* (1990, 341ff.). This begins with the standard modelling of this phenomenon that can be found in any elementary quantum mechanics textbook: a free quantum system ("quanton") with kinetic energy E, on encountering a potential barrier of energy V_0, where $V_0 > E$, still has a finite probability of emerging on the other side of the barrier. This is usually described as a particle "tunnelling through" the barrier. But this is to assume that the free quanton continues its motion throughout, in defiance of its lacking the energy to surmount the barrier. On the contrary, though, as these authors point out, when the quanton encounters the barrier "its stationary state is not identical with that of a free quanton" (LL&B, 345), and it now has a finite probability of having an energy exceeding V_0, and a corresponding finite probability of emerging on the other side of the barrier. Thus the usual account is based on a fiction, since it is only on the supposition that the quanton remains a free particle that talk of its penetrating a barrier is appropriate.

In describing this conceptualization as a fiction, I am going somewhat beyond what Lévy-Leblond and Balibar claim. They assert that in fact "the quanton crosses the barrier by actually 'leaping over' it" rather than by tunnelling through it, as the case of its appearance on the other side of the barrier corresponds to its finite probability of having an energy exceeding the barrier: "If a quanton goes past a potential barrier higher than its energy, it is [not] so much passing 'through' (tunnelling) as passing 'over' (leap-frogging) it: since its stationary state is not identical with that of a free quanton, its kinetic energy has in fact a certain dispersion." (LL&B, 345) But, as will become clear in what follows, I believe that the full implication of their analysis is that even the "leap-frogging" picture should be regarded as fictional, insofar as the state representing this is but one term in a superposition of states. The quanton, that is, loses its identity as a free particle on encountering the potential barrier. Since there is a free quanton on each side of the barrier, it is *as if* it has tunnelled through it or leap-frogged over it, but such conceptualizations of the phenomenon in terms of the motion of a free particle are fictions.

Lévy-Leblond and Balibar, moreover, do not extend this kind of analysis to virtual processes. After an accurate account of the nature of such processes, they conclude that "[given] the nature of the processes considered, the 'virtual' particles are no less 'real' than the classical fields for which they assume the role of the mediator" (LL&B, 126). I shall contend that, by parity of reasoning with the above analysis of quantum tunnelling, we should conclude rather that, although there is indeed a real quantum process mediating the field, the conceptualization of this phenomenon in terms of the exchange of free virtual quanta is a pseudo-explanation. Virtual processes are fictions, but they are not explanatory fictions. For they are as physically impossible as Ptolemaic epicycles: although supposing them may aid in calculations, it does not aid in explaining the phenomena in question.

2. Quantum Tunnelling

In the most elementary treatment of this effect one treats the incoming quanton as being in a stationary state, that is, in an eigenstate of its total energy, and encountering a potential barrier of height V_0, so that

$$V(x) = 0 \text{ for } x < 0 \text{ and } x > a, \text{ and } V(x) = V_0 \text{ for } 0 \leq x \leq a. \qquad (1)$$

Elementary calculations show that even when $V_0 > E$ the quanton has a non-zero state function inside and beyond the barrier (i.e. for $x > 0$) given by[5]

$$\varphi_E(x) = a'_+ \exp[-\kappa_E' x] \qquad (2)$$

The wave number $\kappa_E' = [2m(V_0 - E)]^{1/2}$, and $V_0 - E$ is positive, so the exponential function has a real argument. Concerning this transmitted “wave”, Lévy-Leblond and Balibar explain,

> It is exponentially attenuating, in fact very rapidly, in the region $x > 0$. There is, therefore a certain probability for the quanton to penetrate ‘inside’ the wall of the potential, since the probability density is not zero. (LL&B, 317)

This result extends to the case of a barrier of finite width *a*. The quanton has a finite probability of emerging on the other side of the barrier even when $V_0 > E$. As we already noted above, this is usually described as a case of the a particle of total energy E “tunnelling through” the potential barrier of energy V_0, where $V_0 > E$. But, Lévy-Leblond and Balibar argue, it would be more accurate to describe this as the particle “leap-frogging” the barrier: “since its stationary state is not identical with that of a free quanton, its kinetic energy has in fact a certain dispersion” (345).

[5] Here, and throughout, I am taking units where $\hbar$ (*h*-bar) = 1.

> We observe that in this case … the quanton, when it is in a proper state of its total energy, is not in a proper state of kinetic energy, since its potential energy is not constant. Its momentum spectrum consists of a distribution width $p \approx \kappa'$, due to the presence of the exponential terms $\exp[\pm\kappa' x]$ in the wavefunction…. The corresponding kinetic energy spectrum includes components of (kinetic) energy greater than V_0, revealing the existence of non-zero probability amplitudes, for which the quanton has enough energy to go 'over' the top of the barrier. (345-46)

The analysis that supports these claims is given by them earlier in the textbook (LL&B, 318-19). The wave function for the stationary state of a free quanton corresponds to a probability amplitude in momentum with just two peaks, at $p = \pm\, p_{\mathbf{E}}$. But the wave function for the transmitted part of the wave can be expressed as a superposition of plane waves,

$$\varphi_E(x) = a_+'\exp[-\kappa_E' x] = A \int \exp[ipx]\,\bar{\varphi}_E(p)\mathrm{d}p \qquad (3)$$

where $\bar{\varphi}_E(p)$ represents "the transition amplitude from the stationary state of energy E of the *non-free quanton* to the state having wavefunction $\exp[ipx]$, in other words, to the momentum proper state of the *free quanton* characterized by the proper value *p.*" (318) This probability amplitude can be calculated to be

$$\varphi_E(p) = \text{const.}/(p - i\kappa_{\mathbf{E}}'), \qquad \kappa_{\mathbf{E}}' = [2m(V_0 - E)]^{1/2} \qquad (4)$$

giving a probability density of

$$\sigma_E(p) = |\text{const.}|^2/(p^2 + \kappa_{\mathbf{E}}'^2) \qquad (5)$$

While this probability distribution extends from $-\infty$ to $+\infty$, it has non-negligible values in the interval $\kappa_{\mathbf{E}}' = [2m(V_0 - E)]^{1/2}$. This means that "although the quanton has a well-defined energy (proper) value, it can in principle, as long as it is under the influence of a potential step, assume *all* possible values of the momentum, and hence all possible values of the energy of a free quanton." (LL&B, 319)

In this connection, however, it is noteworthy that the momentum of the transmitted quanton,

$$p'_E = \pm [2m(E - V_0)]^{1/2} = \pm\, i\, \kappa_E' \qquad (\text{where } \kappa_E' = [2m(V_0 - E)]^{1/2}) \qquad (6)$$

is *imaginary* for $V_0 > E$. This would correspond to a negative kinetic energy, which is not physical. This observation will be of importance later in my argument.

The situation, it seems to me, is as follows. The exponentially attenuating state function (2) is a real function, representing a real probability of the quanton's being found on the other side of the barrier. But if we imagine it as representing a transmitted particle, the particle has imaginary momentum and negative kinetic energy. It is not, therefore, a real particle. As is often the case in quantum theory, it is better to resist visualizing what is going on in terms of particle trajectories, and to accept the genuine novelty of quantum processes. When the quanton approaches the barrier from one side, it has various probabilities of being found on the other side as a free quanton with a given momentum. The case is similar with a quanton in a potential well: it does not bounce back and forth between the sides of the well, as a classical particle would, but has a spectrum of states with corresponding periodicities.

Nevertheless, one can still use the Heisenberg relations to estimate depths of penetration and times of transitions. Since the probability of transmission is only significant within the range $\kappa_{\mathbf{E}}' = [2m(V_0 - E)]^{1/2}$, the depth of penetration is approximately $\Delta x \approx 1/\kappa_{\mathbf{E}}'$ or less, corresponding to a breadth of the momentum distribution of $\Delta p \approx \kappa_{\mathbf{E}}'$. Likewise, for the corresponding breadth of the kinetic energy spectrum of the quanton, $\Delta E \approx \kappa_{\mathbf{E}}'^2/2m$, the duration of the penetration is approximately $\Delta t \approx 1/\Delta E = 2m\Delta x/\kappa_{\mathbf{E}}'$ or less.

Of course, this is an idealized representation, where the quanton is represented by a stationary state, a one-dimensional plane wave, and the potential barrier by a step function. One can perform a more realistic analysis not only by regarding the quanton as a "wave packet", but also by using spherical waves in three-dimensional space. But the principle remains the same. Indeed, by replacing the block potential (1) by a potential $V(x)$ (> E) that continuously varies between x_1 and x_2, one may derive (LL&B, 348-350) a general formula for the transmission probability $\mathscr{T}$ for a quanton at x_1 to "tunnel through" to x_2:

$$\mathscr{T} = \exp[-2 \int \kappa(x)\, dx], \qquad \kappa(x) = [2m(V(x) - E)]^{1/2} \qquad (7)$$

with the integral taken between x_1 and x_2. For a constant potential V_0 across $a = x_2 - x_1$, this reduces to

$$\mathscr{T} = \exp[-2\kappa a], \qquad \kappa = [2m(V_0 - E)]^{1/2} \qquad (8)$$

One of the earliest successes of quantum theory was the application, by George Gamow in 1928, of this "tunnel effect" to explain alpha decay. The alpha particle may be regarded as contained within a potential well between the nuclear potential and the repulsive Coulomb potential. In order to escape it must be transmitted through the latter. For the nucleus of an atom of uranium $_{238}U$ the maximum height of the repulsive Coulomb potential at the edge of the nuclear well can be estimated to be about 30 MeV (LL&B, 351). This far exceeds the energy of the alpha particles this radioactive nucleus emits, which have an energy of about 4.3 MeV. The finite (but very small and rapidly attenuating) transmission probability explains the possibility that the alpha particles (assumed as preformed inside the nucleus) may emerge on the other side of the potential barrier.

As Lévy-Leblond and Balibar explain (LL&B, 354), one can estimate the effect by supposing the alpha particle to be oscillating between the walls of the well with a velocity of about $v \approx 10^7$ m s^{-1}, in a nucleus of diameter about 7 x 10^{-15} m, giving a characteristic time of $\Delta t \approx 7 \times 10^{-22}$ s. The relation between the transmission probability and the average half-life τ of the nucleus is given by

$$\tau = \mathscr{T}^{-1}\Delta t \approx 7 \times 10^{-22} \text{ s} \qquad (9)$$

Using (8), $\mathscr{T}$ may be estimated at approximately 2.3 x 10^{-39}, giving an estimate for the half life of the uranium atom for alpha decay of approximately 3 x 10^{17} s, or 10^{10} years. This is in surprisingly good agreement with experiment given the simplicity of the model.

That success by itself, however, is no argument for a realistic interpretation of the conceptualization of the process involved. Indeed, as the authors admit, the idea of a preformed alpha particle scuttling back and forth inside the nucleus is "just a convenient picture" (LL&B, 354). In this respect, of course, the situation is no different from that encountered in quantum theory from its very beginnings. The electrons in the Bohr model of the atom cannot be interpreted classically as charged particles orbiting in trajectories, since they would continuously radiate and fall into the nucleus; nor could they be interpreted as particles moving in precisely defined trajectories according to the new quantum theory of Heisenberg, Schrödinger and company, since that would involve their simultaneously having determinate values of position and momentum (or orbital angular momentum and angle), in contradiction to the Heisenberg inequalities. The Bohr model was, nonetheless, a "convenient picture", since it enabled the successful prediction of the Rydberg formula, and gave an explanation of sorts of why only certain orbits were possible in terms of the quantum of action. With the advent of quantum theory proper, we are now in a position to see why this fictional model worked to the extent it did. Provided the orbits are conceived as corresponding to most probable energy states of the electrons in their bound state, rather than trajectories of orbiting particles, there is no contradiction with quantum indeterminacy.

A comparison with the case study by Bokulich (2009) of closed orbit theory may be useful here. She details how highly excited atoms (known as Rydberg atoms), when subjected to strong magnetic fields, were found in the 1980s to display resonances in the absorption spectrum beyond the ionization limit. This is anomalous, in that this limit corresponds to the outermost electron being torn off; one would expect in that case that no more energy could be absorbed, as is indeed the case in the absence of the strong magnetic field. What Karl Welge and his group at Bielefeld discovered, however, was that the complex and irregular looking absorption spectra, when Fourier-transformed into the time domain, revealed an orderly set of strong peaks that corresponded perfectly with the transit times of electrons following closed, classical trajectories. Calculations revealed only about 65 such orbits resulting from the interference of incoming and outgoing waves, and these correspond very accurately with the displayed resonances. Thus the explanation for the anomalous resonances is that "the Rydberg electron is allowed to continue to absorb energy, so long as that energy is precisely of an amount that will propel the electron to the next trajectory allowed by the interference pattern."[6] But, of course, it is acknowledged that "electrons do not, in fact, follow classical trajectories at all—they are fictions."(101)

[6] This is quoted by Bokulich from Von Baeyer 1995, 108 (Bokulich 2009, 100).

The explanation for the success of this semi-classical model is that the "classical" behaviour is chaotic, and chaos only appears as "a long-time ($t \rightarrow \infty$) phenomenon that on short time-scales can still look orderly" (101). It therefore appears only in high resolution experiments, which involve a precise determination of energy, so that the action involved is far in excess of the quantum of action. Thus quantum principles are used to justify a semi-classical effect, for which there is as yet no purely quantum theoretical calculation.

The situation for closed orbit theory is thus analogous to that of Bohr's atomic model based on the Old Quantum Theory. That was used successfully for a number of years to predict various quantum effects very accurately, despite its being based on a fiction. Both therefore count for Bokulich as *explanatory fictions*, models that do "give some genuine insight into the way the world is and … have some genuine explanatory power" (Bokulich 2009, 103). In each case there are salient features of the model that "exhibit a pattern of counterfactual dependence on the elements represented in the model", allowing one to predict, for example, "how the oscillation peaks would have been different if the closed trajectories had been altered in various sorts of ways" (106).[7] The difference between the two cases is that by the end of the 1920s, the fiction of classical trajectories of the Bohr model "which had indeed been a fruitful scaffolding, had been eliminated in favor of what we would call the true description of the behavior of electrons in atoms" (107), whereas there does not yet exist a fully quantum explanation for the anomalous resonances in Rydberg atoms.

With these examples in mind, let us return to the Gamow model of alpha decay, which pictures an alpha particle oscillating between the nuclear potential and the repulsive Coulomb potential before penetrating the latter and being emitted. Although the conceptualization of it as an oscillation of a "free" alpha particle inside the nucleus is clearly a fiction, there is enough structural similarity between this fiction and a more rigorous quantum theoretical representation to ground the calculation of the half life: the real quantum physics involves a "beat phenomenon" with the same characteristic

[7] Bokulich explicates what is to count as an explanatory fiction in terms of a *structural model explanation*: this is "one in which not only does the explanandum exhibit a pattern of counterfactual dependence on the elements represented in the model, but, in addition, this dependence is a consequence of the structural features of the theory (or theories) employed in the model." (Bokulich 2009, 106)

frequency as imagined in the bouncing particle scenario, in keeping with a quantized action specific to this phenomenon, and these are sufficient to support the success of the “intuitive” calculation.

Things are otherwise, though, with the second part of the Gamow model, which envisions a free alpha particle penetrating the barrier. For while in the Bohr model the trajectories of orbiting particles can be reconceived as peaks in the spatial probability densities corresponding to most probable energy states, there is no such reinterpretation of the trajectory of an alpha particle through or over the potential barrier that is consistent with quantum principles. For if the state function (2) is interpreted as describing a trajectory of a particle, the particle has an imaginary momentum. This is because it does not represent a free particle with a definite state of kinetic energy, but a quanton in a bound state within a potential barrier, with a resulting spread of possible kinetic energy values. If, on the other hand, the state function is interpreted as a superposition of states as in (3), these states are also not states of free particles that either do or do not penetrate the barrier, but transition probability amplitudes for a quanton to emerge on the other side of the barrier with these momenta.

Thus quantum theory allows us to understand the success of Bohr’s semi-classical model, and also that of closed orbit theory, as well as the limits of application of such a model: it also allows us to understand the computational success of the oscillating alpha particle aspect of the Gamow model. In contrast, there are no quantum principles that allow us to interpret terms of the expansion (3) as representing particle trajectories. Moreover, since there is a well-understood quantum theoretical explanation of the “tunnelling” phenomenon that does not share any structural similarity with these aspects of the fiction, we should conclude that tunnelling, as it is generally conceived, is a mere fiction, a fruitful scaffolding that should now be eliminated.

3. Virtual Processes

Now, it might be thought that I have made a little too much of the case of barrier penetration. But, as Lévy-Leblond and Balibar astutely observe, it “is scarcely an exaggeration to say that *every* specifically quantum phenomenon can be interpreted in terms of the tunnel effect.” (LL&B, 350) This is certainly the case for the standard model of exchange forces in particle physics, thus connecting the case of quantum tunnelling with that of virtual forces. On this model, the force binding the nucleons together in the nucleus of an atom is understood in terms of an exchange of π mesons, or pions. Now, for a free pion to be created from a nucleon is in conflict with the principle of the conservation of mass-energy, but such an exchange can be understood in terms of the tunnel effect as follows. An extra amount of energy, at least $V_0 = m_\pi c^2$, where m_π is the rest mass of the free pion, is needed in order for a pion to be created from a nucleon. But now this energy may be interpreted as the height of a potential barrier separating the two nucleons when they are close together, and we may invoke the tunnel effect to explain how the pion has a finite probability of penetrating this barrier to be absorbed by the other nucleon. The pion must have a total energy of zero, so that its momentum may be computed from the relativistic formula

$$E = [p_\pi^2 c^2 + m_\pi^2 c^4]^{1/2} = 0 \qquad (10)$$

giving

$$p_\pi = [-m_\pi^2 c^2]^{1/2} = i\kappa_\pi, \text{ with } \kappa_\pi = m_\pi c \qquad (11)$$

We see that here, as in the case of tunnel effect, when we interpret the process in terms of the propagation of a particle, we have a particle with imaginary momentum and negative kinetic energy, here corresponding to the requirement that $-V_0 = -m_\pi c^2$. This explains, of course, how it is that the nucleons experience an *attractive* force by *emitting* and *absorbing* a particle: if the particle had a real momentum, they would be repelled from one another. On the 1-dimensional model, the attractive potential would be proportional to $\exp[-\kappa r]$, where r is the characteristic distance between the nucleons; on a 3-dimensional model it is rather $\exp[-\kappa r]/r$, the famous Yukawa potential (LL & B, 371-72). The range of this force is of the order of $a = 1/\kappa$, or, reintroducing the dimensional constants, $a = \hbar/m_\pi c$. So, just as we were able to make a good intuitive estimate of the lifetime of $_{238}$U using the admittedly fictional model of an alpha particle oscillating in a potential well and then penetrating the Coulomb potential barrier, so here we are able to make a good intuitive estimate of the range of the nuclear exchange force on the fictional model of an exchange of a virtual pion. Each of these cases is supported by solid physics, where the existence of an exponentially attenuating state function allows a process that would be prohibited *if there really were a particle transmitted through the barrier*.

The same kind of analysis would evidently apply in the case of Hawking radiation. Hawking himself conceives this to occur as follows. He notes that fields in empty space will be subject to certain quantum fluctuations. He conceives these fluctuations "as pairs of particles of light or gravity that appear together at some time, move apart, and then come together again and annihilate each other" (Hawking 1988, 106). Energy conservation dictates that if one of these particles has positive energy, the other must have negative energy: "The one with negative energy is condemned to be short-lived because real particles always have positive energy in normal situations. It must therefore seek out its partner and annihilate with it." (106) The gravitational field inside a black hole, however, "is so strong that even a real particle can have negative energy there." (106) "It is therefore possible, if a black hole is present, for the virtual particle with negative energy to fall into the black hole and become a real particle or antiparticle." (106) "The positive energy of the outgoing radiation would be balanced by a flow of negative energy particles into the black hole." (107)

As should by now be clear, all this talk of pair production and the absorption of a negative energy virtual particle by the black hole is superfluous. The situation is entirely analogous to that of alpha particle emission by a uranium nucleus described above. Here it is the strength of the gravitational potential within the Schwarzschild radius that exceeds the energy of the escaping quanton, rather than the Coulomb potential of the nucleus; nonetheless, there is, according to the quantum "tunnel effect" described above, a finite probability of the emergence of a quanton from just inside the black hole. When it is emitted with an energy E, the black hole will correspondingly have a reduction in energy (and spin, etc.) by the same amount.

There are many further difficulties with the idea of virtual processes that have been ably pointed out by other commentators. Chief among these, as succinctly pointed out by Bunge in his 1970 article, is the justification of virtual particle creation and annihilation in terms of "the Heisenberg uncertainty relation"

$$\Delta E \cdot \Delta t \geq h/2 \qquad (12)$$

There are in fact several objections to such a justification. First, the "ignorance interpretation" of quantum probabilities is known to be in error, and the indeterminacy implicit in quantum theory does not depend on the existence of human observers. The interpretation of Heisenberg's relations as concerning "uncertainty" in our knowledge is therefore an incorrect epistemological interpretation of a genuine ontological relation. Thus Hawking says of the value of a field and its rate of change that "the uncertainty principle implies that the more accurately one knows one of these quantities, the less accurately one can know the other." (Hawking 1988, 105). In fact, the Heisenberg relations relate spreads (or mean standard deviations) of values in conjugate dynamical variables of a quantum system, like position and momentum, or angle and orbital angular momentum. The relations are not a principle, but inequalities derivable from the first principles of quantum theory, as H. P. Robertson first showed (the Heisenberg inequalities are a special case of what is now called the Robertson-Schrödinger relation). In connection with this, as Bunge insists, it is simply bad philosophy to assume "that a law of nature, such as energy conservation, can be violated as long as no one is observing" (Bunge 1970, 507). Second, time is not a dynamical variable. One can get around this to some extent by being careful to define t in association with a dynamical variable v of a system in a non-stationary state; then an analogue of (12) can be derived where Δt is the quotient of the standard deviation of v by the absolute value of the rate of change of its expectation value, that is the time after which its expectation value changes appreciably.[8] Third, if we are dealing with a stationary state, there is no spread in its values, and ΔE is identically 0. As Bunge observes, it is therefore unjustified to interpret ΔE as the energy of a virtual quanton and Δt as the duration of the virtual process (507).

It may be appreciated, however, that Lévy-Leblond and Balibar were careful not make these errors in the analysis I have repeated above. Instead, ΔE is interpreted as the spread in the spectrum of values of the kinetic energy corresponding to the momentum expansion (3), and the lifetime of the process is related to Δt through the

[8] See Mandelshtam and Tamm 1945.

transmission probability by the equation (9). Perhaps for this reason, they staunchly defend the reality of virtual processes:

> These intermediate quantons are often called ‘virtual’, in view of their ‘abnormal’ energy properties, as opposed to ‘real’ quantons, which can be observed and manipulated experimentally. This distinction is somewhat formal; it is a classical habit to consider these ‘virtual’ quantons as having properties which are ‘not real’. The quantum theory clearly demonstrates the possibility of the existence of these non-classical states. Moreover, from the empirical point of view, the distinction is hard to sustain. From the exchange of a pion between two nucleons, the ‘virtual’ existence of which lasts 10^{-24} s, imparting to it a large negative kinetic energy—of the order of its mass—to the exchange of an electron between two protons in the H_2^+ ion, with negative kinetic energies of a few electron volts, right up to quantons considered as being ‘real’ which, [by] all accounts, have no more than a transitory existence between the accelerator which produces them and the counter which absorbs them, there is no absolute distinction possible. (LL&B, 373)

On the contrary, I would suggest that there is a perfectly straightforward distinction: real processes have real momenta and positive kinetic energy: they are on the mass shell. Relatedly, the terms in an expansion of the state function as a superposition of states do not represent real processes: they represent probability amplitudes for transitions to states representing such processes. The times of the interactions is an irrelevant factor here; so is the fact that the quantum states in the superposition do indeed exist. What is in question is whether these quantum states can be interpreted as processes of particle exchange. I suggest that the answer is implicit in these authors’ account of quantum tunnelling. The idea that there is a particle that tunnels through a potential barrier is parasitic on the notion that the free quanton that emerges on the other side of a potential barrier was in fact “there” inside the barrier earlier. But there is no free quanton (having its own energy eigenstate) inside the barrier: inside the uranium nucleus or black hole, the quanton has no individual identity. In each case, the supposition that the state function corresponding to transmission through the barrier represents a particle results in the unphysical situation where the particle has an imaginary momentum.

Further, the supposition that the individual terms in the expansion represent free quantons is incompatible with the idea that the (bound) state of the quanton is a superposition; as Lévy-Leblond and Balibar say of the original example of tunnelling, the superposition represents "*all* possible values of the momentum, and hence all possible values of the energy of a free quanton." (LL & B, 319)

This negative verdict thus extends to the realistic interpretation of Feynman diagrams. I will not go into details here, since this case has been well analyzed by others.[9] As is well known, on this model higher order terms in the expansion of a state function in terms of probability amplitudes for transitions are interpreted as representing virtual processes of increasing complexity. Thus the first term can be regarded as representing the exchange of a virtual photon; the second as the exchange of two photons, another as the emission of a photon that disintegrates into an electron-positron pair which then mutually annihilate into a photon that is absorbed, and so forth.[10] Here the utility of Feynman's diagrams for facilitating computations is not in question. But the interpretation of them as representing individual particle trajectories certainly is. As Robert Weingard has objected, the individual terms in a superposition cannot be interpreted as representing individual particle trajectories without running into inconsistencies: for "neither the number nor the kinds of virtual particles are sharp in the superposition" (1988, 45ff.) Accordingly, as Michael Redhead has remarked, "to invest them with philosophical significance is like asking whether the harmonics really exist on the violin string" (1988, 20). Tobias Fox, in his recent review article on the status of virtual processes, rates this as the one argument that is adequate to undermine the interpretation of virtual processes as real: "only the argument of superposition is sufficient to disprove a status of real—i.e., space–time-like existence of virtual particles: (2008, 41). That is, if one accepts that virtual processes are, by definition, off-mass-shell, then this superposition argument is still sufficient to undermine their realistic interpretation.

Thus my analysis seems to be in complete accord with Fox's. He writes:

[9] See in particular Weingard 1998, Redhead 1998, and Fox 2008.
[10] For an acute analysis of the notion of 'representation' involved here, see Meynell 2008.

> All in all, virtual particles do not exist. They are not even instruments to make a physical theory work … . They are instruments to give an intuition of mathematical rules. … It is, however, possible to calculate the values of ‘‘range’’ and ‘‘life-time’’ in a given system (interaction). Such calculations are not meaningless in the sense that they are consistent with physical laws. But they are not—and this is a crucial point—tools to describe an individual trajectory of a distinct virtual particle which in addition would be testable experimentally. (Fox 2008, 48)

4. Conclusion

I have argued here that virtual processes are *mere fictions* by giving a thorough analysis of the phenomenon of quantum tunnelling. The process known as “quantum tunnelling” certainly occurs. But the implied conceptualization of it as a free particle burrowing through a potential barrier is flawed. Rather it is because the quanton is not a free particle, but in a bound state in a potential associated with a certain energy, that it has a dispersion, a range of values of energy states with corresponding probability values; and because of this that there is a finite probability of a particle emerging on the other side of the barrier. The term in the state function corresponding to the transmitted “wave” cannot be interpreted as representing a free particle, since the particle would have an imaginary momentum and negative kinetic energy. Thus there are no alpha particles existing as free particles inside the nucleus of a uranium atom that then “burrow through” the massive potential barrier of the repulsive Coulomb potential. Regarding the alpha particle as oscillating in the nucleus is a useful fiction for calculating the half-life of the process, but it is no more realistic than Bohr’s electron orbits conceived as particle trajectories. What one can say is that an expansion of the state function in terms of alpha particle bound states yields a finite (but extremely small) probability of an alpha particle appearing on the other side of the barrier.

This analysis extends fairly straightforwardly to the model of nuclear forces in terms of an exchange of virtual particles. Here the rest mass of the pion may be interpreted as a potential barrier preventing a process whereby, for example, a proton decays into a neutron plus a pion, and a neutron absorbs the pion to be come a proton. If this is interpreted as the exchange of a virtual pion (virtual, because the interaction is forbidden by mass-energy conservation), then the pion has, again, negative energy and imaginary momentum. But the same process may be reconceived in terms of transition probabilities between the bound states of the nucleons without invoking this physically impossible model. Moreover, since the state function in question will be a superposition of states, interpreting these states as virtual processes will require there to be not one but infinitely many such processes, thus precluding a consistent picture.

Again, the same kind of analysis can apply to Hawking radiation. There are fluctuations of the field just inside the Schwarzschild radius of a black hole. Associated with these is a finite (but extremely small) probability that a field quanton, either a photon or a graviton, may emerge as a free particle outside the black hole, despite its lacking the energy (classically) to escape the gravitational field of the black hole. There is absolutely no need for fanciful appeals to clouds of virtual particles hovering around the event horizon, or for illegitimate appeals to a time-energy indeterminacy relation to justify unobservable violations of mass-energy conservation.

To reiterate, I am not arguing that there are no such phenomena as alpha decay or Hawking radiation. What I am objecting to is the conceptualization of them as involving particle processes occurring with definite energy states. In each case, it is argued, the phenomenon can be understood in terms of a finite probability of transmission predicted by quantum theory, without appealing to particle trajectories. The idea that a particle "penetrates" a barrier that it does not have the energy to surmount, or that a pair of particles is "virtually" produced one on either side of the Schwarzschild radius, in defiance of energy conservation, should be discarded as unphysical. Virtual processes, I conclude with Bunge, are at best "computational intermediaries" (Bunge 1970, 508); understood as the actual trajectories of particles, they are, like particles tunnelling through potential barriers, mere fictions.[11]

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