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ON THE 'EMPTINESS' OF PARTICLES IN CONDENSED-MATTER PHYSICS

ABSTRACT. In recent years, the ontological similarities between the foundations of quantum mechanics and the emptiness teachings in Madhyamika–Prasangika Buddhism of the Tibetan lineage have attracted some attention. After briefly reviewing this unlikely connection, I examine ideas encountered in condensed-matter physics that resonate with this view on emptiness. Focusing on the particle concept and emergence in condensed-matter physics, I highlight a qualitative correspondence to the major analytical approaches to emptiness.

KEY WORDS: Emptiness, Madhyamika–Prasangika Buddhism, quantum mechanics, condensed-matter physics

1. INTRODUCTION

"Thus atoms are like empty space-they have no real existence" (Shantideva, 8th cent, 1997).

Recent years have witnessed a surge of interest in the exploration of intersections between western science and Buddhism. This exciting trend is exemplified by the several excellent books which have appeared on this subject (Mansfield, 1995; Wallace, 1996, 2003; Gyatso, 2005). The pervasiveness of the Buddhist notion of emptiness in the foundational structure of quantum mechanics is compellingly presented from several different angles in these and other references. In this paper, I briefly review the concept of the particle in traditional quantum mechanics, before examining some philosophical implications of condensed-matter physics in the context of emptiness. I argue that the notion of the particle in condensed-matter physics can serve as a good illustration of the analytical approaches to 'emptiness' as expounded by the Madhyamika–Prasangika school of Buddhism. This work does not attempt to establish an isomorphic equivalence between Buddhism and quantum physics; such an effort would be misguided and ultimately incompatible with the notion of emptiness itself.

That there should be a convergence at all between science and Buddhism may strike some as unlikely. Science is still often viewed (even by its practitioners) as an essentially materialistic enterprise, diametrically opposite in its world view to the insights gained from spiritual practice. It is true that the starting points of western science and Buddhism could not be farther apart, the former restricting its purview to the 'external', objective world mapped out by instrumental measurements, and the latter focusing mostly on the 'internal', experiential world explored through meditation. Thus, I find it truly amazing that at a deeper level there should emerge a profound resonance, and perhaps even a consistent world view. Yet fairly recent advances in physics have revealed just that. In the words of Harlem–Renaissance thinker Jean Toomer: *"While the world produced by science, the technical, industrial world, is growing more materialistic, science itself is growing more immaterial"* (Johnson, 2003). Perhaps Buddhists will not be too surprised that ever more careful 'external' observations should eventually reveal glimpses of the true nature of reality, emptiness.

2. EMPTINESS IN MADHYAMIKA BUDDHISM AND THE ORTHODOX INTERPRETATION OF QUANTUM MECHANICS

> "The universe appears to consist of discrete objects that have an existence from their own side. These objects appear to exist in themselves as stars, planets, mountains, people, cars, and so forth, all 'waiting' to be experienced by conscious beings. Normally it does not occur to us that we are involved in any way in the existence of these phenomena. [...] As we shall see, the truth is very different." (Gyatso, 2000, p.108)

I will not try to do justice to the Buddhist explanations on emptiness, filling many volumes, and refer instead to highly qualified contemporary sources (Gyatso, 1986, 1988, 1992, 2001). The teachings on emptiness go back to Buddha Shakyamuni, the historical Buddha. Later, Nagarjuna, founder of the important Madhyamika school, and then Chandrakirti of the Prasanga school, extensively elaborated on the subject. Here, I merely give a brief synopsis of the main ideas that go back to the Madhyamika–Prasangika school.

Emptiness negates the notion that the objects of our perception exist independently, that they have an inherent objective reality from their own side, that the world exists as it appears to us independent of our perception. Rather, everything is correctly seen as dependent-arising, as ultimately lacking any independent existence. Ontologically, our understanding of any object does not equate to an understanding of the sum of an object's parts. Every phenomenon owes its present existence to other phenomena but is not reducible to those phenomena. Nothing exists inherently without being subject to change because everything depends on causes and conditions. The belief in an immutable identity of phenomena such as the self is seen as an delusion.

Emptiness is central in Buddhist thought, its deep realization being the hallmark of a liberated being. There are many analytical approaches to emptiness. These are sometimes referred to as *inferential cognizers*, and are the precursors to a direct, non-conceptual realization of emptiness we have to rely on conceptual reasoning to point us in the direction of emptiness. In *Heart of Wisdom* (Gyatso, 1986) – a commentary to the Buddha's *Essence of Wisdom Sutra* – five such approaches to emptiness are identified; for the purposes of this paper I will only mention the first three.

The first approach stresses the ephemeral nature of all phenomena and their strong dependence on causes and conditions. Here the argument is that if an object existed from its own side, it could never change in time, nor could it give birth to, or interact with other phenomena. It would be completely unobservable. In reality, nothing is free-standing, because everything exists in dependence on its cause and gives rise to its effect. In the second approach, we can contemplate how every phenomenon depends upon having been named or labeled. In some instances, it is readily apparent that the object first came into existence by the process of naming, as for example when a new government agency is born or a new law is passed. According to the Madhyamika–Prasangika school, we are encouraged to consider all phenomena as depending on their designation in this way.

A third approach to realizing emptiness is the systematic deconstruction of an object into its parts (and parts of parts), and upon putting them back together never finding the object's true identity. The object is seen as a mere collection of characteristics, none of which contain the identity of the object. The collection itself depends on the presence of all the parts, and therefore it cannot become the singular, monolithic entity that our mind projects on this collection. These various approaches to emptiness should be considered complementary and ultimately interdependent, although they may appear distinct to a conceptual mind.

Emptiness runs completely counter to our usual mode of thinking. We normally envision the world around us as made up of things that all exist more or less as they appear and do not fundamentally depend on anything else for their existence. When objects interact, the interaction leaves the individuality and the discreteness of the participating objects intact. This worldview was long espoused by western science which saw the universe as a collection of discrete objects (stars, planets, comets, etc.) evolving in time according to mechanical laws, and interacting via external forces or fields. When Einstein thought about the universe, he saw *"this huge world, which exists independently of us human beings and which stands before us like a great eternal riddle, at least partially accessible to our inspection."* (Schlipp, 1949, p. 5)

In the 1920s, it gradually became clear to the scientific community that the microcosm was governed by "strange" laws that diverged radically from anything then known to science. Quantum mechanics – the theory that eventually emerged from the initial perplexity and confusion that atomic measurements brought about – undoubtedly represented a scientific revolution, as it forced a radical reorientation of the way scientists viewed the physical world. Its proper philosophical interpretation is still somewhat in dispute in the physics community, even though no one doubts its basic validity. In fact, no other theory in physics has been subjected to more meticulous experimental scrutiny, and no other theory has proven so exact and reliable in its predictive power (Feynman, 1988). So what does modern physics tell us about the "reality" of elementary particles?

A major lesson from quantum mechanics is that particles are not to be thought of as point-like, solid entities. They are not tiny indivisible marbles. Rather, they take different forms in different observational contexts. Sometimes an electron appears as a point-like particle, sometimes as a wave smeared out over large regions of space (the *wave-particle duality*). Sometimes, it takes the form of a "cloud" around an atomic nucleus.

Furthermore, electrons and likewise other elementary particles do not follow a classical orbit or trajectory. In one formulation of quantum mechanics, the electron follows all possible trajectories at once (Feynman, 1988). In another, due to the uncertainty principle, a definite path is seen as an altogether meaningless construct when applied to microscopic particles. Heisenberg's original formulation states that we are fundamentally forbidden from knowing both the position of a particle and its momentum at the same time. We can only know one or the other, never both.

At first, one might believe that the uncertainty principle is just a reflection of our ignorance, that the particles really do have definite positions and momenta at all times, but that quantum mechanics just does not reveal them. This view was championed by adherents of the so-called *hidden-variables* hypothesis. Hidden-variable proponents, including Einstein, considered quantum mechanics an incomplete theory, because it did not yield all that there was to know. For them, the description left out half of "reality".

It must be emphasized that local hidden-variable theories have since been refuted. Careful experimental measurements (Aspect et al., 1982) testing Bell's inequality (Bell, 1964, 1966) – an amazing theoretical accomplishment which suggested a way to discriminate between the two positions- settled the matter in quantum mechanics' favor. A detailed and illuminating discussion of Bell's inequality is given in Mermin (1985), as well as in Mansfield (1989). Attributes of a microscopic particle, like position and momentum, are called *observables* in quantum mechanics. The formalism of quantum mechanics requires uncertainty principles between many, but not all, pairs of these observables. This means that we cannot know them all simultaneously, and that they do not all have what we might call "simultaneous reality".

We can summarize the situation as follows: before a measurement of an *observable* is taken, the observable has no definite value; it is simply not defined. Apparently, the act of measurement plays a very special role in quantum mechanics: it forces the system under investigation into a definite state where it did not have any before. In technical terms we say that a measurement *collapses the wave-function*. Thus, in quantum mechanics, there is no such thing as a non-intrusive, non-invasive measurement. All measurements produce the outcome, or better they condition the kinds of outcomes that are possible. As soon as a measurement is made, the clean separation into observer and observed vanishes. A complementary result, referred to as *contextuality* (Mermin, 1993; Greenstein and Zajonc, 1997), is that the value of an observable can depend on the other observables of the object that are measured or known.

Another striking consequence of quantum mechanics was pointed out by Einstein et al. (1935) in the famous Einstein–Podolsky–Rosen (EPR) thought experiment. Here two elementary particles are produced so that they form part of an *entangled* two-particle state and proceed to fly-off in opposite direction, which ensures that after some time they will be far separated in space. It would seem that both particles, being many light-years apart, could be reasonably thought of as having separate identities. This view, however, turns out to be incorrect.

Instead microscopic particles that have interacted and become entangled cannot be considered separate entities in any meaningful way. A measurement taken in one place has an impact light-years away at an instant. This is what is meant by the *non-locality* of quantum mechanics. The relationship between entangled particles, their common state, is more important than their individuality. When we consider what cosmology teaches us, we can appreciate how much of our physical universe should be entangled over large distances. This points to a radical interconnectedness imposed by quantum mechanics and by direct consequence a lack of separate identity. This conclusion is very reminiscent of the Buddhist notion of universal connectedness, or *Interbeing* (Hanh, 1997).

3. INSIGHTS FROM CONDENSED MATTER P HYSICS

"We are not suggesting that a sprout and a fire have no characteristics or nature of their own. What we mean is that these characteristics are not intrinsic to those objects, because then the fault would arise that since these characteristics would be independent of any affecting factors, the object [...] could never transform into anything else or cease to exist." (Gyatso, 1992, p. 68)

3.1. *Emergence*

It should be noted that quantum mechanics may not be the final physical theory, although certain aspects of it, like non-locality, will have to be preserved in any future theory (Mansfield, 1989). In fact, traditional quantum mechanics has already been refined by quantum field theory, which is compatible with the theory of special relativity. Quantum field theory also has uncertainty principles built into it, analogous to the ones discussed earlier, but it clarifies the relationship between elementary particles and fields.

Generally speaking, we can say that in quantum field theory the lingering dichotomy between particle and field is thoroughly overcome. Particles appear as localized manifestations of their corresponding field, and they continuously come into and go out of existence. Furthermore, the essence of a particle is seen as inseparable from its interactions. The ephemeral nature of particles finds its ultimate realization in the concept of *virtual particles*, responsible for mediating interactions between other particles. In fact, even a perfect vacuum is seen as teeming with such virtual particles.

Condensed-matter physics, which incorporates techniques and concepts from quantum field theory, is often sidestepped by philosophers of science, probably due to the explicitly phenomenological approach built into its theoretical descriptions. Theories are often acknowledged without hesitation to describe only limited aspects of an infinitely more complex world. On the other hand, condensed-matter physics provides an epistemological link between the "strange" world of quantum mechanics, the world of a few atoms, and our experienced macroscopic world. At its heart, the field studies what happens when atoms aggregate and form matter on the macroscopic scale. Is it possible, we ask, to predict the properties of a collection of atoms from the quantum-mechanical properties of the single atoms.

The short answer is no. The material properties of graphite are quite different from those of diamond, even though both are made from carbon atoms exclusively. Generally, the organizational structure of the constituent particles is much more important than the properties of the particles in isolation. As an illustration, consider probably the most basic characteristic of a solid – its solidity. If you took the solid apart one atom at a time, none of the individual atoms would exhibit any notion of solidity. As discussed, single particles lack this very attribute. We are forced to recognize the solidity of matter as an emergent phenomenon which depends not so much on what particles aggregate, but ultimately on the fact that they do.

We can say that the properties of materials that we perceive depend on the organizational principles underlying them: the symmetry of the crystal lattice, or the absence of long-range periodicity. The way liquid water appears to us – its viscosity, density, surface, color, for instance – is emergent in nature. Other measurable quantities would include the thermal and electrical conductivity of water, the speed of sound and light through it, its compressibility, its boiling and freezing point, etc. These are all collective phenomena which cannot be found in the properties of an individual water molecule. It makes no sense to speak of the viscosity of a molecule.

The emergent nature of reality as we perceive it becomes even more startling when we consider universality – a central notion in the study of phase transitions. It states that certain key features of phase transitions are the same in a large class of systems differing widely in their microscopic structure. In a certain sense, the microscopic details – the precise inter-atomic potentials, the scattering behavior, say – can be quite insignificant in determining how the macroscopic object will change phase, how it will reorganize itself on a global scale.

Conversely, phase transitions are purely macroscopic phenomena, and their sharp onset increasingly smears out as the system is made smaller and smaller. A chunk of iron has a well-defined magnetization and a well-defined Curie temperature above which this magnetization vanishes. A tiny chip of iron – a quantum dot – lacks both a stationary magnetization, as fluctuations become non-negligible, as well as a precise onset temperature. A robust magnetization is therefore only exhibited in macroscopic samples.

On the basis of both universality and emergence, it would appear impossible to predict the detailed properties of condensed matter from the known behavior of its constituent parts. Universality, loosely speaking, suggests that there is no one-to-one correspondence between the microscopic processes and macroscopic observables, and emergence insists that these observables lose their meaning entirely at the microscopic or even mesoscopic level. This situation is what Laughlin (2005) calls nature's "walls of scales". The rules operating at the macroscopic level cannot be deduced from the ones at the microscopic level. As he points out, not one of the 11 distinct crystalline phases of water ice was predicted from first principles. In this sense, a strict hierarchy dissolves: the rules of sociology are not reducible to those of human psychology, the two sets being disjoint but equally valid in their respective domains, and psychology is not reducible to neural science, and so on all the way "down" to quantum mechanics.

Emergence is perhaps particularly compatible with the analytical approach to emptiness which stresses the relationship between whole and parts. In this approach, we search for the origin of an object's identity in its parts. For example, we could ask what the real nature of water is. Is it to be found in its parts, i.e. in the individual water molecules? None of water's attributes, however, are inherent in the water molecule, as we saw earlier. Next we ask whether it is found in the collection of parts. Can water be equated to the collection of individual water molecules? Emergence holds that "more is different" (Anderson, 1972). The properties of water emerge from the collection of water molecules but they cannot be reduced to the microscopic rules of molecular interaction. A collection of 50 water molecules does not make a tiny droplet of liquid water; it does not exhibit sharply delineated phases and therefore cannot have a well-defined liquid phase. The attributes of liquid water only arise in the macroscopic limit. This statement may seem somewhat mysterious. One might ask: when do we have enough water molecules assembled, and what changes between 50 and that number? The answer must lie in the rules of statistical mechanics by which macroscopic certainty is constructed from microscopic randomness and fluctuation.

In summary, water is also not equal to the collection of its parts. A collection of water molecules is not yet water. However, without water molecules there is no water. Consequently, water is neither to be found in its parts, as the collection of its parts, or outside its parts; we cannot locate its identity anywhere. Buddhists conclude that water is empty, i.e., it does not exist inherently at all.

3.2. *Generalized Particles*

Evidently the quantum mechanics of a few particles does not allow us to predict properties of a large collection of particles. Is it nevertheless possible to understand some measurable properties of materials, say the color, electrical conductivity, or heat capacity of a crystal, from the principles of quantum mechanics? The answer has to be at least partially affirmative, as this is precisely what condensed matter physics aims to do. We will see that in the process new particles are postulated, and a refined notion of the particle emerges – one that resonates very strongly with the three approaches to emptiness outlined earlier.

Consider a crystal such as a grain of table salt. We can think of all the sodium and iodine atoms as arranged on a regular lattice. It turns out, however, that the lattice of atoms itself is less important in understanding many macroscopic properties of salt than the excitations that can happen on this lattice. One class of such excitations are crystal vibrations. These lattice vibrations cannot be thought of as classical waves, like ripples on a pond, but must be treated as quantum particles themselves (see, for instance, Ashcroft and Mermin, 1976). The energy contained within a single-frequency acoustical wave comes in discrete energy packets. As such these energy packets are termed *phonons* in close analogy with the photon or light-particle. The analogy between these two particles runs deeply, but on first sight there is one major difference. In contrast to the photon, which can travel in vacuum, it is immediately clear that the phonon has only a "relative" reality. It exists only in dependence upon the underlying lattice. It is a particle built on top of particles, in a sense. If we take away the "actual" atoms and their interactions, the phonon vanishes as well.

Nevertheless, the phonon acts just like any other quantum particle; it has an associated momentum (here *crystal momentum*) and energy, and it can scatter off impurities in the crystal or off other phonons. More importantly, without the phonon as a conceptual entity, the macroscopic and thermodynamic properties of solids cannot be understood. Condensed matter physics is built on many such particles, or *quasi*-particles as they are sometimes termed, including the *magnon*, the *exciton*, the *polaron*, and the *plasmon* (Maradudin and Nardelli, 1969; Kittel, 1987). Other types of excitation may yet be singled out and given a particle name by the physics community.

These particles all share this explicitly relative existence: they emerge as entities embodying the various dynamical degrees of freedom of the underlying atomic lattice. Furthermore, upon investigation into their theoretical origin, these condensed-matter particles quickly reveal themselves as a form of imputation based on mathematical reasoning, and their elusive reality is dependent on having been designated and singled out for naming. Yet, these particles can be inferred from a variety of macroscopic measurements and thus (in the spirit of the "Middle Way") cannot be deemed non-existent altogether.

So the rules of quantum mechanics can successfully be brought to bear on the crystal problem. It is important to remember, however, that quantum mechanics is invoked not in the description of the particles making up the crystal, but rather in the description of the new, generalized particles governing the dynamics on the lattice. Without a lattice there cannot be lattice dynamics, and so the nature of these generalized particles is explicitly relative or contextual.

As a related example, consider the conduction electrons inside metals. Such an electron is not the exact same particle as its counterpart in free space. It is sometimes called a *dressed* electron, as it interacts with the sea of other electrons and can distort the ionic lattice, thereby permanently carrying with it some positive screening charge. The crystal lattice distortion induced by the electron is seen in the quantum-mechanical description as an interaction of the electron with phonons. In this picture, the electron emits and then quickly reabsorbs a phonon. We may still call the particle an electron, but in reality it has transformed through this phonon interaction into a different particle with a different effective mass and charge. In an ionic crystal, such conduction electrons are often given another name – polarons, codifying this transformation.

In semiconductors, electrons excited into the conduction band leave behind *holes*, the absence of an electron, which must be treated as a particle on equal footing with the electron. The motion of these holes is essential in the workings of a transistor, for instance. An electron can even become bound to a hole, creating a hydrogen-like entity called an *exciton* with its own excitation spectrum. If electrons and holes have equal ontological status in the crystal context, as implied by the notion of an exciton, we can appreciate how elusive the electron's identity must be.

As we saw, an electron in a metal transforms by its interaction with a phonon, renormalizing its properties like mass and charge. In addition, there is a closely-related effect that gives rise to superconductivity. Instead of an electron emitting and reabsorbing the phonon, one electron emits the phonon and another electron absorbs it. In effect, two electrons exchange a phonon and thus interact with one another. In free space, two electrons interact via exchange of virtual photons and repel each other, but in the lattice environment we can also have the exchange of phonons which – according to the Bardeen–Cooper–Schrieffer (BCS) theory (Bardeen et al. 1957) – actually gives rise to an attractive interaction. At low temperatures, two electrons (near the Fermi energy) can thus become bound to one another, forming a new entity called a *Cooper pair*.

So what exactly is a Cooper pair? To start, a Cooper pair must be recognized as a very different entity from the single electron, even obeying a different quantum statistics; the Cooper pair is a *boson*, whereas its constituent parts are *fermions*. Very analogously, Cooper pairing between atoms in liquid Helium-3 transforms these atoms from fermions to bosons and makes possible the formation of the superfluid.

So the Cooper pair is not of the same nature as its constituent parts – electrons. It is clearly more than just two electrons. The bound nature of the two electrons is essential, which means that the phonon must be an integral part of the description of a Cooper pair. Is a Cooper pair then the collection of two electrons and a phonon? Again, we would have to say no. In essence, the Cooper pair cannot be understood by considering the constituent parts individually. In describing the phenomenon, it is not enough to identify which entities participate, it is equally important to see how they relate to one another. This relation is particularly striking here, as the phonon acts as a virtual particle, being emitted by one and quickly absorbed by the other electron before it could ever be observed directly.

Such examples may serve as an illustration of the connection between the three approaches to emptiness. Speaking to the approach based on whole and parts, we argued that the Cooper pair is not to be equated with a collection of two electrons and a phonon, the phonon being a virtual particle here. The approach emphasizing dependence on causes and conditions of all phenomena is illustrated by the role of the phonon as an indispensable participant in bringing to life the entity we call a Cooper pair. The phonon (along with the hole) can be considered as the quintessential manifestation of dependent-relatedness. Phonons and holes are both many-body phenomena that only exist in dependence on the lattice; they are generalized particles that explicitly owe their existence to the aggregation of matter. Lastly, implicit in the identification and construction of this kind of particle, there is the mental imputation of a singular entity and its designation as a particle.

Interestingly, these condensed-matter particles can become building blocks for composite entities. The hole is an integral part of an exciton, and the phonon is involved in both the polaron and the Cooper pair. One could perhaps relegate these particles to the purely conceptual realm, were it not for the fact that the microscopic reorganization into Cooper pairs, for instance, has drastic macroscopic consequences. A superconductor is formed with its vanishing electrical resistance. Another striking example of such a transformation, or phase transition, is the phenomenon of *Bose–Einstein condensation*. At very low temperatures, a gas of atoms can condense into a communal state where the individual character of the atoms is fully overcome. The atom vanishes, and in its place a single entity comprised of tens of thousands of "former" atoms arises.

These examples from modern condensed-matter physics illustrate how malleable and impermanent the particle concept is. Phonons are emitted and absorbed by electrons, electrons transform into Cooper pairs, electrons and holes coalesce into excitons, atoms spontaneously condense into a single condensate. At the same time, reality as we observe it is nevertheless manufactured from those concepts in very measurable ways. A p-type semiconductor conducts electricity via the motion of holes, lattice imperfection do not scatter Cooper pairs unlike single electrons (hence the vanishing resistance of a superconductor), and the heat conductivity through crystals is limited by phonon scattering in ways which can be precisely quantified.

One can thus argue that within condensed-matter physics the nuanced compromise of the Buddhist middle way between realism and nihilism, between inherent existence and non-existence, finds perhaps its most intuitive scientific illustration. In the context of condensed-matter physics, the 'dependent-arising' nature of the particle is readily appreciated. Furthermore, the close relationship between the main approaches to realizing emptiness, the teachings on dependent-arising, the mental deconstruction of the whole into parts, and the role of designation, may be understood by way of example.

One manifestation of emptiness is the emptiness of singularity and plurality (Gyatso, 2001, p.267f). The emptiness of singularity follows from an object's decomposition into parts or alternatively from its dependent-arising nature. Since the notion of plurality is conversely imputed on the basis of seeing many singular parts, plurality too lacks inherent existence. The particles encountered in condensed-matter systems evoke this seeming duality between singularity and plurality. When emphasizing the function of the particle we stress singularity, and the particle appears elementary. When emphasizing the nature of the particle we stress plurality, and it appears composite. However, the nature and function of these particles cannot be cleanly delineated. Both aspects depend on one another and neither perspective is the inherently true way to conceive of the particles. Ultimately, the duality vanishes because both aspects of the particle are empty of inherent existence.

4. CONCLUSION

In the Heart Sutra Buddha Shakyamuni says: "*Form is emptiness, emptiness is form.*" Buddhism teaches that ultimate reality embodying emptiness does not exist above or separate from conventional reality (Gyatso, 2001, p. 275f) . It is in the objects of our perception that emptiness manifests. No higher realm of existence, no transcendental reality is postulated, other than emptiness. This subtle point, I believe, is also echoed in the quantum world. It would be wrong to think that electrons, protons, or phonons did not exist at all. They positively exist as abstractions or designations within "conventional reality". However, when we look for the particles' "ultimate reality", when we investigate their ontological or epistemological basis, we find that they are less substantial than we first guessed. We find that nature does not conform to our conceptualization of it. One could say that the very nature of these particles, the set of all their observed attributes, arises out of their emptiness.

In a sense, modern physics has advanced in two opposite directions, represented by two of its dominant sub-fields: elementary particle and condensed matter physics. The former aims for a consistent theory for the most basic building blocks of matter (elementary particles), whereas the latter finds quantum particles arising as *emergent* phenomena from strongly interacting systems. Despite these fundamental differences both branches arrive at similar philosophic notions of the particle: it is seen as a concept that exists conditionally and not inherently, but which is nevertheless a useful idealization with direct consequences for our physical world.

Nonetheless, elementary particle physics is a champion of the reductionist paradigm (for instance, Weinberg, 1993), where the "true" laws are sought in ever more microscopic processes. Condensed-matter physics, in contrast, has more fully adopted the notion of emergence. There is an implicit acknowledgement that not one set of laws could describe every possible phenomenon in the universe, but that different "realities" arise across different scales of complexity. In the end, it may be condensed-matter physics' emphasis on emergence, reflected in its treatment of the particle, that makes its foundational framework deeply compatible with the notion of emptiness.

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