How does quantum field theory (QFT) contribute to our understanding of gravity? Is there a unified theory that explains both QFT and quantum mechanics?

Quantum field theory is a further abstraction of quantum mechanics.

Let's go through this step-by-step to understand the levels of abstraction.

Quantum mechanics was developed to model empirical outcomes, the most well-known being the double slit experiment. To do this you need to let go of the notion of what objects are. Rather you work backwards from the empirical observation of interference. In essence, interference is understood using wave theory, so we need a wavefunction.

The next step is to note that in the low energy limit, the interference pattern is built up through the accumulation of point-like detections. This is distinctly particle like.

Combining the wave-like propagation with particle-like detection, we have the wavefunction describing a probability amplitude from which the probability of detection can be calculated using the Born rule. This is something that you could easily guess given the empirical data.

The next step is the collapse hypothesis, wherein the wavefunction collapses to a point on detection.

The combination of these factors describes the double slit experiment, but does not explain it. In particular, there is no known mechanism for the collapse hypothesis. This has given rise to the various interpretations of quantum mechanics.

Quantum field theory is a further abstraction of quantum mechanics. It is most accessible in the context of nonrelativistic quantum electrodynamics. Here we start with a classical electromagnetic field and quantise it. In general, the quantum field operators are not so easy to work with. However, what is apparent from the classical theory is that the field can be decomposed into a superposition of modes, each of which can be modelled as a simple harmonic oscillator. The quantum simple harmonic oscillator is a textbook problem that introduces Planck's quanta as the energy packets representing the successive excitation of the mode. These quanta are called photons. However, given the level of abstraction, the properties of the photon are far removed from the properties of a classical particle. The salient point is that in the quantum field theory, particles can be created and destroyed. The field is composed of modes, with each mode having associated photon creation and annihilation operators. The expression of field interactions in terms of creation and annihilation operators is called second quantization. Quantum field theories are second quantized theories. This is simply a further abstraction of quantum mechanics.

The standard model of particle physics is a fully relativistic formulation of quantum field theory. Additional fields were introduced for all the different types of matter. All interactions are mediated by particle exchange.

Ultimately quantum field theories represent the deepest level of abstraction of quantum theory. QFT has in no sense replaced quantum mechanics. Rather QFT is used to analyse high energy particle collisions, which is a pretty niche application. Quantum mechanics is far more commonly used in the development of quantum technologies. Effective field theories are also commonly used in the treatment of solid-state phenomena, so QFT techniques can be applied elsewhere. Furthermore, the level of abstraction is apparent when treating solid-state systems, where a plethora of so-called quasi-particles abound. Such quasi-particles provide an effective means of treating solid-state phenomena, but are in no sense real. One example is lattice phonons, which are quantized vibrational modes of the crystal lattice. It is tempting to think of phonons as particles, as they involve the same second quantization procedure as used with QFT. However, from another perspective, they are simply vibrations of a crystal lattice.

The salient property of quantum field theories is that they all consider field quanta as particles. They are effectively theories of interacting particles. Gravity, when considered as a field, is expected to be a quantum field theory. However, to date, a consistent quantum theory of gravity has not been developed. As such, quantum field theory has failed to provide a deeper understanding of gravity.

The quantization of gravity remains a major theoretical challenge. As successful as our theories are, we expect them to be consistent. We expect quantum theory to ultimately describe the universe. The fact that the theory that describes the large scale features of the universe appears to be incompatible with the theory that describes the smallest scales is a major concern. The apparent incompatibility between quantum theory and gravity may ultimately require a further level of abstraction if they are to be reconciled.

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