Waves, Particles, and Quantum Mechanics

In this brief I am exploring the "Copenhagen Interpretation" in Quantum Mechanics by making the language more precise, thereby avoiding some misconceptions.

Quite frequently we hear the claim, that a particle is both, a wave and a particle. What is the difference?

A wave, in a classical sense, can happen in an extended medium, where different parts of the medium move in different, but correlated ways. Examples are waves on the surface of water, sound waves in air or water, etc.

Particles, on the other hand, are objects, almost point-like.

The early debates between Newton and Huygens were about the nature of light: Is light a beam of particles, or is light a wave extending in space? The observation of interference of light seemed to give Huygens the upper hand.

However, we have never observed parts of a particle at two different places at the same time, showing that a particle itself cannot be a wave.

Then, where does the claim, 'electrons are also waves' come from?

In classical mechanics objects follow Newton's equation of motion. Solving these differential equations yield the General solution considering the mass, the geometry and potentials for the object. To obtain the specific solution one has to satisfy the specific initial conditions of $x=x_o$ and $v=v_o$.

In quantum mechanics the time-evolution for e.g. electrons – or what we can know about electrons - follows the well-known Schrödinger equation: But here the initial conditions are not knowable due to the uncertainty principle, taking care of the fact that not both quantities, x_o and v_o, are knowable at the same time. It follows that the solution of Schrödinger's equation cannot represent position and momentum of the particle, but, as Born et al. stipulated the solution generates only a probability density of finding the object(particle):

$$\rho \quad = (\varphi) * (\varphi^*)$$

If, e.g. you look in a certain volume-element that predicts a probability of 25%, it does not mean you find 25% of that particle in this volume-element, but it means that in 25% of the cases when you look you find the whole particle, whereas in 75% of the cases you find no *particle at all. In human terms: if Barbara spends 20% of her time in Göttingen and 80% of her time in Geneva, you can never find 20% of Barbara in Göttingen.*

This <u>*probability*</u> *can be a continuous function through space and therefore can have wave-character. But remember: the probability itself is not the particle.*
Thus, in the well-known double-slit experiment with e.g. electrons, the interference pattern is determined by the experimental set-up. If you put a photographic plate behind the double-slit, you will see the individual (whole) electrons arriving with probabilities determined by the set-up not by the properties of the electrons. Also, the wave- function may tell you that the electrons with a certain probability came through the left or the right slit, but each electron came only through one of the slits.

> *We can state: Electrons are particles that cannot create interference, but probabilities extend over the whole space and can have wave-character and thus can show interference.*

Questions to answer: What happens to the field of probabilities at the instant you observe the particle at a location x?

A: At that instance all probabilities go to zero except for the observed event at location x, where the probability goes to one. This change happens at once. It is not subject to information travelling at less or equal to the speed of light. Even if initially there was a small chance the particle might have been on Mars, the moment we observe it here, we know it is <u>*not*</u> *on Mars.*

How about the photon?

Experiments show that photons behave the same: In a double-slit-experiment single photons register at the screen and over time the interference picture becomes visible. Thus, again, photons act as particles.
The classical electromagnetic fields can be interpreted as probabilities, not as fractions of some photons.

That would solve one problem more easily, namely that photons get accelerated in a gravitational field, while we do not know, how gravity interacts with classical electromagnetic fields.

Actually, we can interpret the photons the same way: Maxwell's equations give the probabilities with which the time-evolution of the photons proceeds. Experiments confirming the particle nature of photons are the Compton-scattering or the photo-electric effect (electrons knocked out of metal-surfaces by photons).

Einstein, in his 1905 interpretation of the photo-effect claimed that photons were particles of Energy

$$E=h v$$

colliding with electrons in the metal plate, knocking them out. The intensity of light affected only the numbers of photons and thus the number of electrons knocked out from the metal surface, nothing else.

Thus the equivalence is

Electron ←→ *photon*
Probability field ←→ *electric/magnetic fields*