LinkedIn Q&A: Do quantum waves require groups of particles?

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> **Question:** *I'm familiar with neutron reflectometry, but it requires multiple neutrons. Do you know of any paper that proves that a single neutron exhibits wavelike behaviour? Also, can the example you gave of reflectors focusing a single neutron to a point be explained by Feynman path integrals, which seem to offer a completely different interpretation than waves?*

Answer: First, switching that around. What is the source of your impression that quantum wave behavior requires *multiple* particles? If any online training teaches this idea, the coursework needs correcting.

The idea that quantum wave behavior emerges only with *groups* of particles goes against a century of quantum experimentation, quantum technology application, and all schools of quantum interpretation, e.g., Copenhagen or Bohmian. Modeling neutrons as waves began with Fermi, though his paper [1] doesn't mention the point explicitly. It's just assumed by the *lack* of any reference to any need for group dynamics, relying instead only on the behavior of each particular quantum particle. More recent work on lowering the neutron density needed for a sample by using specular (mirror-like) neutron lenses more directly addresses your question [2]. However, I don't think it explicitly mentions lowering the intensity to *individual* neutrons. The paper doesn't bother explicitly because, again, the math doesn't work that way; no bunching or inter-neutron interactions are ever assumed in their model because that's what everyone sees experimentally.

Even Bohm uses waves with his famous elaboration of de Broglie's much older pilot wave concept [3]. It's just that Bohm's waves are disconnected from the particles and "piloting" them, one by one, through one or the other hole. By invoking groups, what you suggest is not Bohmian mechanics, even if pilot waves inspired you. Bose condensations of whole-integer-spin particles are group behaviors, but in that case, the group behavior is *identical* to the wave function of the individual particles.

You mentioned Feynman's QED. You might try reading his delightful little book by that title [4]. QED — which amounts to taking the phased integral of all possible futures of the neutron, with its momentum determining the complex (think helical, it works great) wave frequency — is precisely the version of quantum mechanics that predicts that *individual* particles end up focused by such a curved reflector. For example, in the closely relation double-slit self-interference effect, QED flatly refuses to let the particle "go" through one slit or another in any physically detectable way. If you do add something to detect its path, you get the path, but you also destroy all wave effects [5].

When it comes to the wavelike behavior of single particles, it also doesn't matter whether it's a neutron, an atom, a particle, or some gigantic molecules tens of millions of times more massive than an electron [5][6]. It also doesn't matter whether it's a matter particle — a single fermion, such as an electron or neutron — or a boson, such as a photon, a particle of light. For matter-type entities, you use Schrödinger's time-dependent equation in 3-space to describe the expansion of the wave for *each* particle. For photons, you use Maxwell's ancient but gorgeous equations (Heaviside's version, to be precise) to find the intensities. The only difference is that when the energy driving Maxwell's equations gets extremely low, you have to reinterpret the intensity as a probability [7], just as Born did for Schrödinger's equation [8].

I assume you agree that individual photons, by which I mean the units of electromagnetic energy that quantize both when locally emitted and when locally absorbed, are just as worthy of being called particles as electrons or neutrons? If you are part of a study looking for such effects, you can detect the wave behavior of *individual* photons even with your eye [9]. The individual photons appear to your eye as flashes at *precisely* the point from which they radiate.

That's impossible unless QED determines the photon's path, which, in turn, is indistinguishable at the experimental level from saying it behaves entirely like a wave *except* at the moment of emission and the moment of reception. All those interfering potential histories create interference patterns that look exactly like a wave when interpreted by a frame-based observer with her set of xyzt coordinates.

If she adds enough photons, she can even sample the wave by adding a bit of smoke to reflect *individual* photons and thus end their journeys early. But the concentration of the photons at any one time doesn't matter. Whether it's an intense laser sending lots of photons at once, or a feeble one sending out one photon every second, the image comes out the same. The only significant difference is that you must wait much longer in the second case for the picture to develop fully. So again, the waves impact the outcomes one particle at a time, not as groups.

Electrons have charge and so repel each other. That *does* modify their wave functions. However, be careful since the modification *changes* the existing per-particle wave function rather than creating a wave. Neutrons, atoms, and self-interfering large molecules don't have that. Even at high density, their mutual interactions are so close to zero as not to matter except to create occasional rare collisions.

References

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