Wave-particle duality: suggestion for an experiment

R N Sen
Department of Mathematics
Ben-Gurion University of the Negev
84105 Beer Sheva, Israel
E-mail: rsen@cs.bgu.ac.il

December 21, 2013

Abstract

Feynman contended that the double-slit experiment contained the ‘only mystery’ in quantum mechanics. The mystery was that electrons traverse the interferometer as waves, but are detected as particles. This note was motivated by the question whether single electrons can be detected as waves. It suggests a double-slit interferometry experiment with atoms of noble gases in which it may be possible to detect an individual atom as a probability wave, using a detector which can execute two different types of simple harmonic motion: as a simple pendulum, and as a torsion pendulum. In the experiment, a torsional oscillation will never be induced by the impact of a probability wave, but will always be induced by the impact of a particle. Detection as a wave is contingent on the atom interacting much more strongly with the macroscopic detector as a whole than with its microscopic constituents. This requirement may be more difficult to meet with electrons, protons, neutrons or photons than with atoms.
In his famous *Lectures* [5], Feynman stated that double slit experiments contain the ‘only mystery’ in quantum mechanics. By ‘mystery’ he apparently meant phenomena that could not be understood in terms of classical physics. This failure of classical physics could be traced to wave-particle duality, and wave-particle duality could be illustrated simply, and convincingly, by the double-slit experiment with electrons.

In Feynman’s gedankenexperiment, electrons were detected as *particles* (by a geiger counter or electron multiplier), but traversed the interferometer as *waves*. If one tried to detect which slit an electron went through, the interference pattern was lost. Feynman traced this loss to the position-momentum uncertainty relation.

The passage of a microscopic object through an interferometer may be regarded as an *interaction* which changes the state of the object but not that of the (macroscopic) device. Feynman’s double-slit experiment may then be viewed as a succession of two interactions: (i) the electron-interferometer interaction, and (ii) the electron-detector interaction. In (i), the electron acts like a wave; in (ii), like a particle. The question which does not seem to have been asked is: can (ii) be replaced by an interaction in which the electron, or some other microscopic object, acts like a wave? The answer to this question may be in the affirmative for suitable pairs of microscopic objects and detectors, and the aim of this note is to suggest a double-slit experiment with *atoms* for testing this possibility.

![Figure 1: Testing whether atoms arrive as particles or waves](image)

Figure 1 illustrates the scheme of the experiment and the design of the detector. The left-hand side (a) shows a cross-section of the scheme in the

1Owing to the centrality of the detector to our considerations, we shall restrict use of the term *interferometer* to mean only the system of slits or gratings.

2Note the similarity with external field problems in quantum electrodynamics [7].
(horizontal) $xy$-plane. Here the $z$-axis is normal to the plane of the paper. The right-hand side (b) shows the detector $D$, which is a thin rectangular vane suspended from the top. Here the plane of the paper is the $xz$-plane and the $y$-axis is normal to it. The key point is that the vane must be able to execute two essentially different types of simple harmonic motion: (i) as a simple pendulum in a plane through the $z$-axis, and (ii) as a torsion pendulum around the $z$-axis, the line of suspension of the pendulum at rest.

The vane is set in motion by the impact of an atom. The atoms are sent through the interferometer one at a time.

Assume, now, that interaction between the atom and the detector transfers momentum to the detector but has no other effect upon it; the vane, which was initially at rest, is set in motion. The experiment consists of repeated observation of the motion of the vane caused by the impact of a single atom. After observing the motion caused by the $n$-th impact, the vane has to be brought to rest before the $(n + 1)$-th impact; the experiment is not designed to reveal the interference pattern.

As one sees from Fig. 1(a, b), the two slits are symmetrically placed with respect to the central vertical axis of the vane. Therefore the single-particle probability distribution $|\psi|^2$ at the vane will be symmetric with respect to this axis. If the vane ‘sees’ $|\psi|^2$ much as the human eye sees ripples on the surface of a pond, then the momentum transfer to the vane ought to be symmetric about its central axis (along the little arrow through the vane shown in Fig. 1(b)). The vane will then be set in motion as a simple pendulum, in the $xz$-plane of Fig. 1(b).

If, on the other hand, the vane ‘sees’ the atom as a particle (striking at the point marked by bullets in Fig. 1), the atom will impart to it: (i) a torque around the $z$-axis; and (ii) linear momentum, along the plane of the vane (see Fig. 1(b)). The resulting motion of the vane will be a superposition of two motions: (i) oscillation as a torsion pendulum around the $z$-axis; and (ii) motion as a simple pendulum in the plane of the vane (the $yz$-plane).

The above can be rephrased (somewhat loosely) as follows. In the experiment described above, the detector will respond differently to waves and

---

3We are assuming that the only motion that the vane can execute relative to the line of suspension is torsional oscillation. This is an assumption on the coupling between the vane and the suspension.

4The idea of using such a device was inspired by the Nichols radiometer, the torsion balance used by Nichols and Hull [9] to demonstrate the pressure of electromagnetic radiation in 1901. The effect was observed independently by Lebedev [8] in the same year.
to particles. If it is struck symmetrically by a wave, it will never execute torsional oscillations; if struck by a particle, its motion will always have a component of torsional oscillation. The angular frequency of a torsion pendulum is \( \omega_t = \sqrt{k/I} \), where \( k \) is the torque constant of the suspension wire and \( I \) the moment of inertia of the vane around its axis of suspension. The angular frequency of a simple pendulum is \( \omega_s = \sqrt{g/L} \), where \( L \) is the length of the suspension. That is, \( \omega_s/\omega_t = \sqrt{gI/kL} \). The experimenter has considerable control over the parameters \( I \) and \( L \). By varying them, it should be possible to control the relative sensitivity of the detector to waves and to particles.

If the vane is struck by a particle (from one of the slits) close to normal incidence and sufficiently close to its centre, the motion that results may be indistinguishable, within experimental error, from that resulting from the impact of a wave. This contingency will not arise if the angle \( \theta \) is large enough, which will be assured if the distance between the plane of the slits and the detector at rest is not much larger than the distance between the slits, as shown in the figure. Furthermore, this distance will have to be large enough so that the moving vane does not collide with the interferometer. Finally, the experiment will have to be carried out in a high vacuum, so that the vane is not subject to random impacts from atoms and molecules in the environment. Under these conditions, motion of the vane will be essentially undamped, so that a method of resetting it to zero after every impact may also have to be devised.

If, as described above, the atom interacts with the vane as a wave and not as a particle, one may say that it interacts with the vane as a whole.\(^5\)

Put differently, the interactions of a microscopic object with a macroscopic one may be of two kinds. The first kind would consist of interactions of the microscopic object with atomic and sub-atomic constituents of the macroscopic object – the vane, in the experiment suggested. The second kind would consist of interactions of the same microscopic object with the macroscopic object as a whole. If interactions of the first kind are dominant, the vane will see the incident object as a particle. It will see the incident object as a wave only if interactions of the first kind are weak, qualitatively speaking, by comparison with those of the second kind. This condition may

---

\(^5\)Chapter 7 of the book *Particle Metaphysics: A Critical Account of Subatomic Reality* by Brigitte Falkenberg is devoted to ‘Wave-particle duality’. The author does not seem to have considered the possibility mentioned in the above paragraph.
be difficult to meet if the microscopic object is an elementary particle such as an electron, proton, neutron or photon which interacts quite strongly with other elementary particles. However, if it is an atom of a noble gas (e.g., He\(^4\)) with a long de Broglie wavelength (without much penetrating power), the chances of success may improve quite considerably. As the experiment could not have been suggested before the advent of atom interferometry, it is fitting to refer the interested reader to a recent detailed survey of the subject [3].

The existence of interactions of the second kind may be regarded as aspect of quantum nonlocality in nonrelativistic physics.

If the experiment succeeds, and one can follow the motion of the vane with sufficient precision, it may be possible to tell whether both kinds of interactions are simultaneously at work. Observation of photons behaving simultaneously as waves and particles have been reported by Foster et al [6]. However, these authors appear to have been motivated not by Feynman’s comments, but by the Bohr-Kramers-Slater attempt of 1924, before the advent of quantum mechanics, to reconcile the wave and particle properties of radiation [1]. For details, the reader is referred to an article by Carmichael [2], one of the authors of [6].

Acknowledgements I would like to thank Samir Bose, Richard Kerner, Hansjörg Roos, Michael Revzen and Geoffrey Sewell for reading and criticizing earlier versions of this note.

References

[1] Bohr, N, Kramers, H A and Slater, J L. The quantum theory of radiation, *Phil Mag* **47**, 785–802. Reprinted in B L van der Waerden (1967). *Sources of Quantum Mechanics*, Amsteradam: North-Holland. Reprinted (2007) by Dover Books, New York.

[2] Carmichael, H J (2007). Quantum fluctuations of light: A modern perspective on wave/particle duality, pp 183–212, in: J Evans and A S Thorndike, eds, *Quantum Mechanics at the Crossroads*, Berlin: Springer, The Frontiers Collection.

[3] Cronin, A D, Schmiedmayer, J and Pritchard, D E (2009). Optics and interferometry with atoms and molecules, *Rev Mod Phys* **81**, 1051–1129.
[4] Falkenberg, B (2007). *Particle Metaphysics: A Critical Account of Sub-atomic Reality*, Berlin: Springer, The Frontiers Collection.

[5] Feynman, R P, Leighton, R B and Sands, M (2006). *The Feynman Lectures on Physics, Definitive Edition*. Vol III, Quantum Mechanics, San Francisco: Pearson Addison Wesley.

[6] Foster, G T, Orozco, L A, Castro-Beltran, C M and Carmichael, H J (2000). Quantum state reduction and conditional time evolution of wave-particle correlations in cavity QED, *Phys Rev Lett* **85**, 3149-3152.

[7] Jauch, J M and Rohrlich, F R (1955). *The Theory of Photons and Electrons*, Reading, MA: Addison-Wesley.

[8] Lebedew, P (1901). Untersuchungen über die Druckkräfte des Lichtes, *Annalen der Physik* **311**, 433–458.

[9] Nichols, E F and Hull, G F (1901). A preliminary communication on the pressure of heat and light, *Phys Rev* **13**, 307–320.