Wave-particle duality and indeterminism in QM:

measurement versus free evolution
and
interpretation

Wave-particle duality in QM:

• objects behave as (“look” like) **particles** because you detect them in a precise location
- particle or localized nature revealed by measurement -

• but move like **waves** while you aren’t looking... one “sees” evidence of wave like interference in the locations they are detected
- wave (delocalized) nature must be unperturbed by measurement -

What is this?

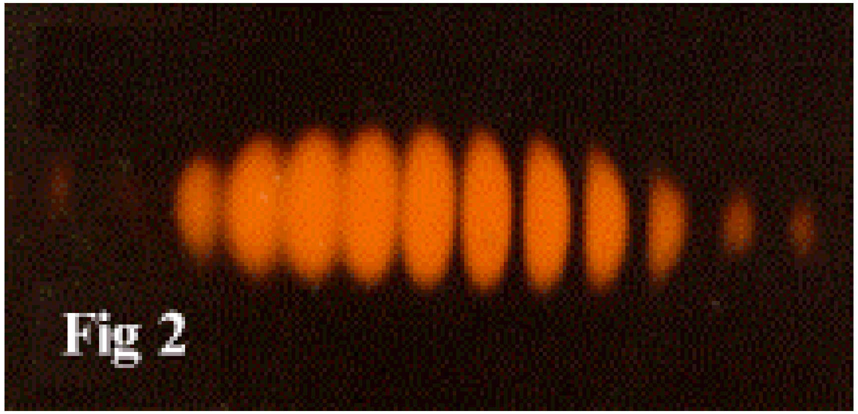
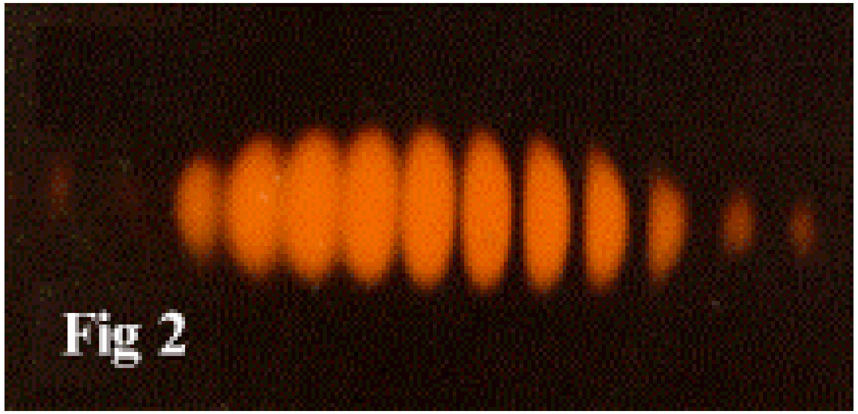
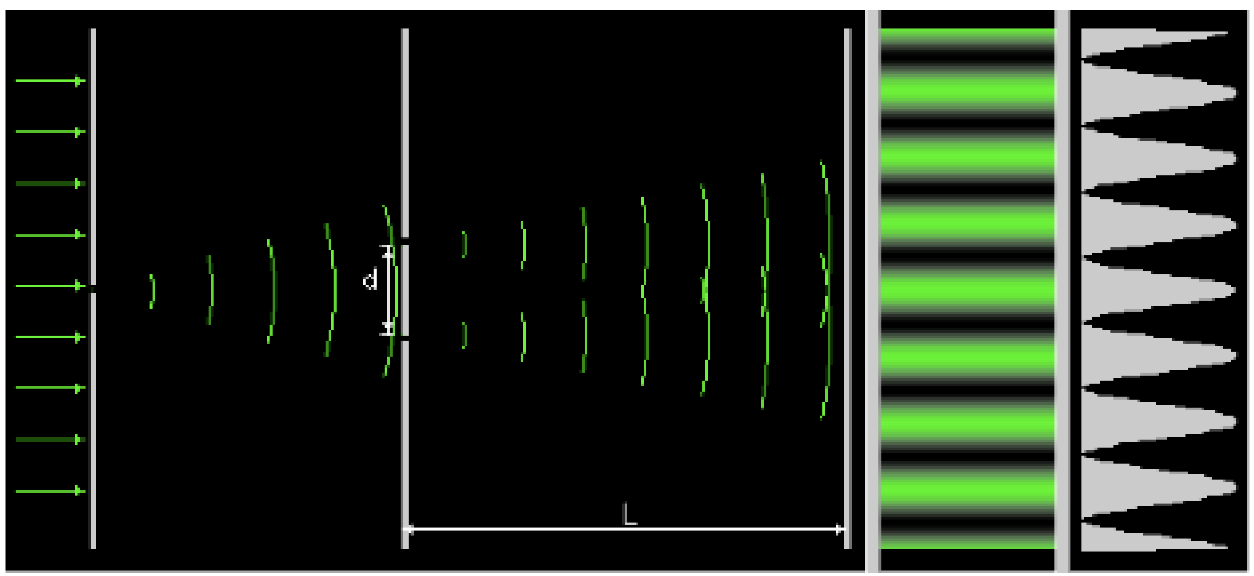


Fig 2

What is this?

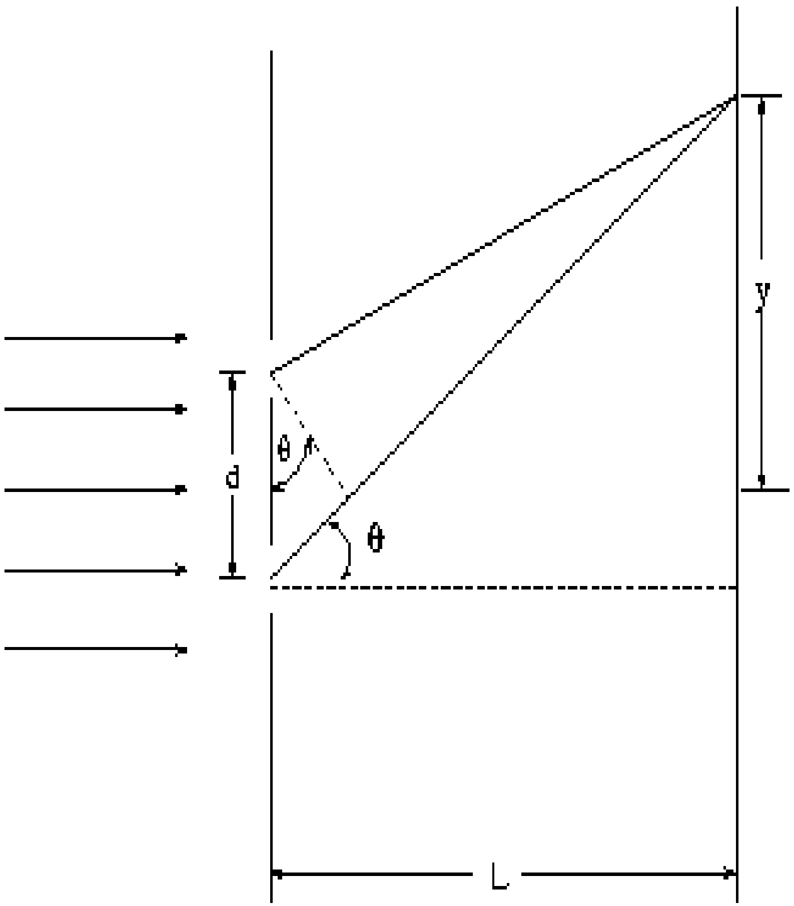


An interference pattern from
Young's Double Slit Experiment



Interference: Light consists of WAVES

Light Interference occurs because of the two paths which generate two wave amplitudes



Differential optical path length

$$r_2 - r_1 \approx d\sin\theta$$

Intensity maxima: constructive

$$d\sin\theta = m\lambda, \quad m = 0, \pm1, \pm2, \ldots$$

Intensity minima: destructive

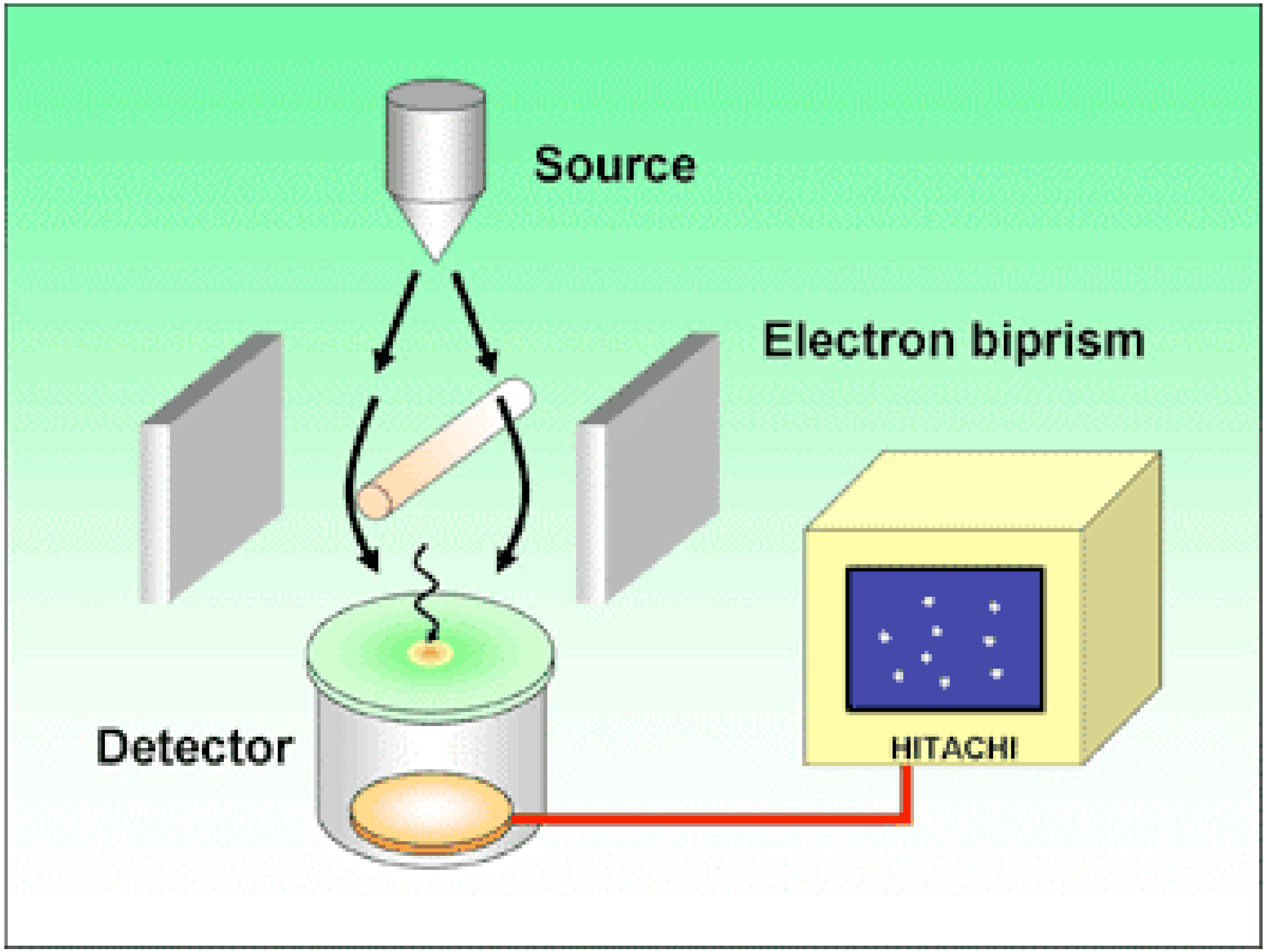
$$d\sin\theta = (m + \tfrac{1}{2})\lambda, \quad m = 0, \pm1, \pm2, \ldots$$

Interference is seen for monochromatic light
all photons have same wavelength

Now perform the same experiment with electrons

single electrons are detected after they are emitted and travel through the biprism

source emits only on e- at a time into apparatus so no two particle interactions



Experiment by A. Tonomura of Hitachi Corp., June 1999

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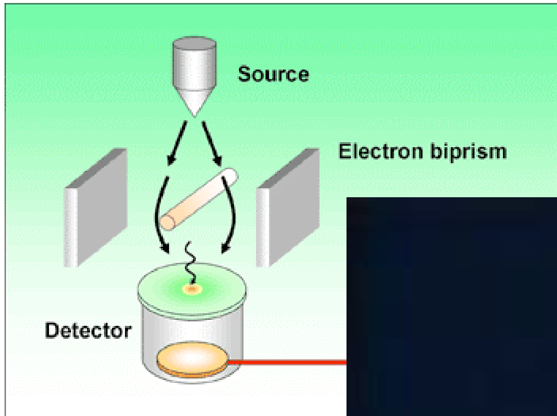


movie of e- detection

single electrons are detected after they are emitted and travel through the biprism

source emits only on e- at a time into apparatus so no two particle interactions

interference occurs because each electron goes on both sides of the biprisim

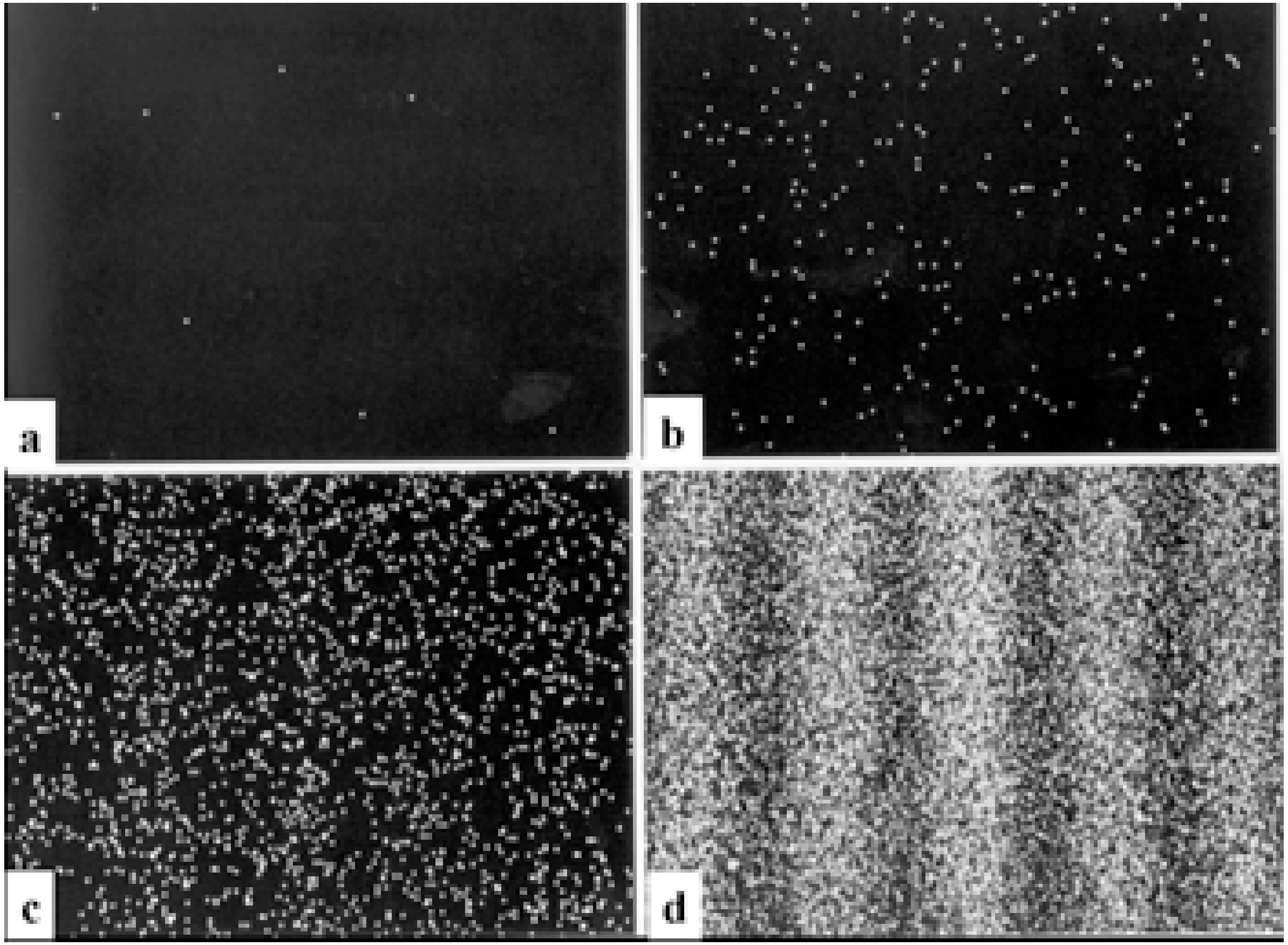
time lapse movie over 20 minutes

each e- appears to land at a random spot

after many events are accumulated, a pattern is revealed

http://www.hqrd.hitachi.co.jp/em/doubleslit.cfm

What can we conclude about the electron from the Tonomura experiment?



Electrons appear to have both particle-like and wave-like properties!

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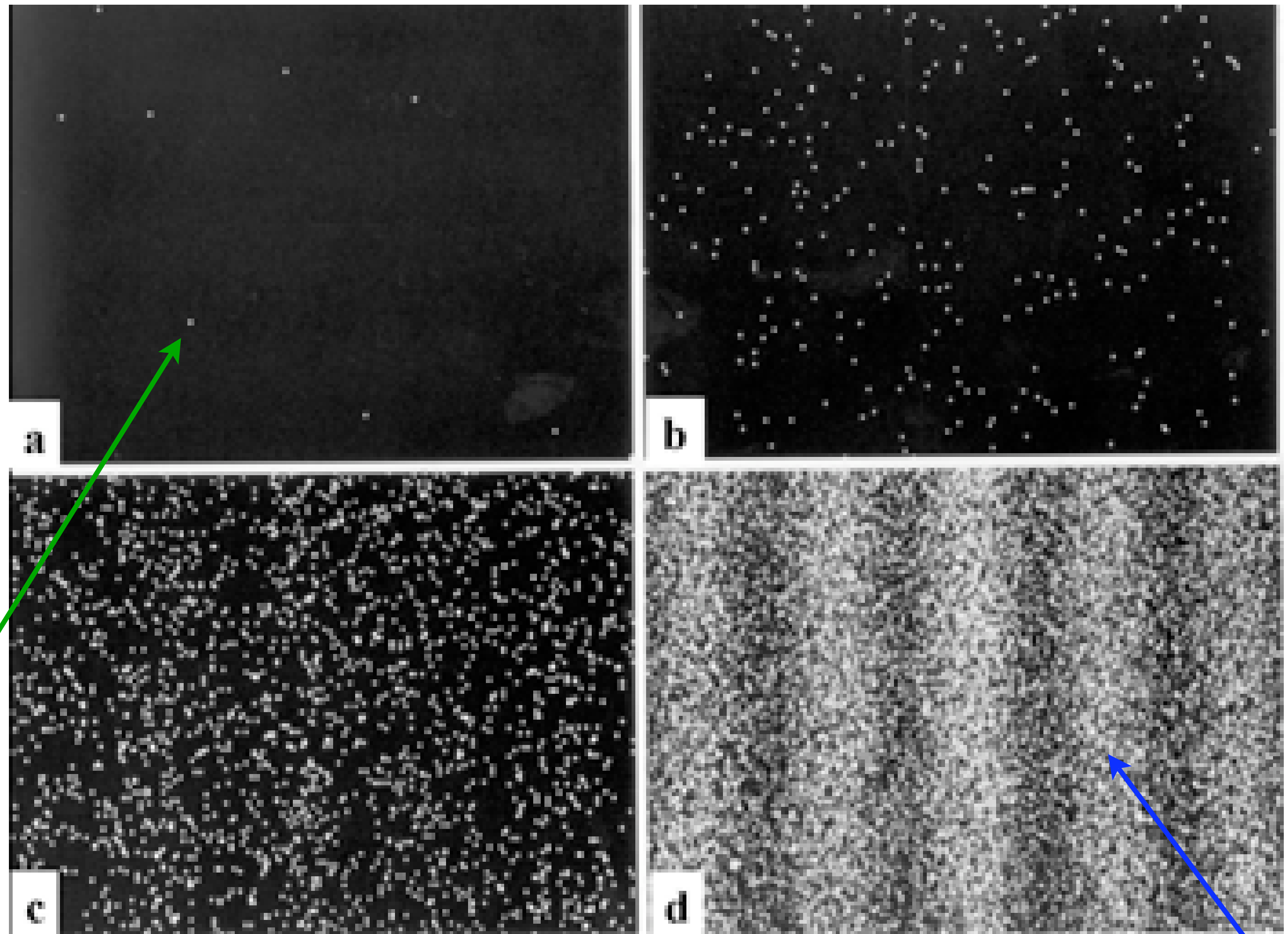
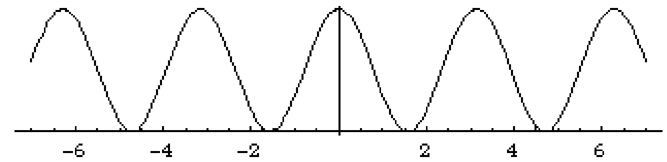


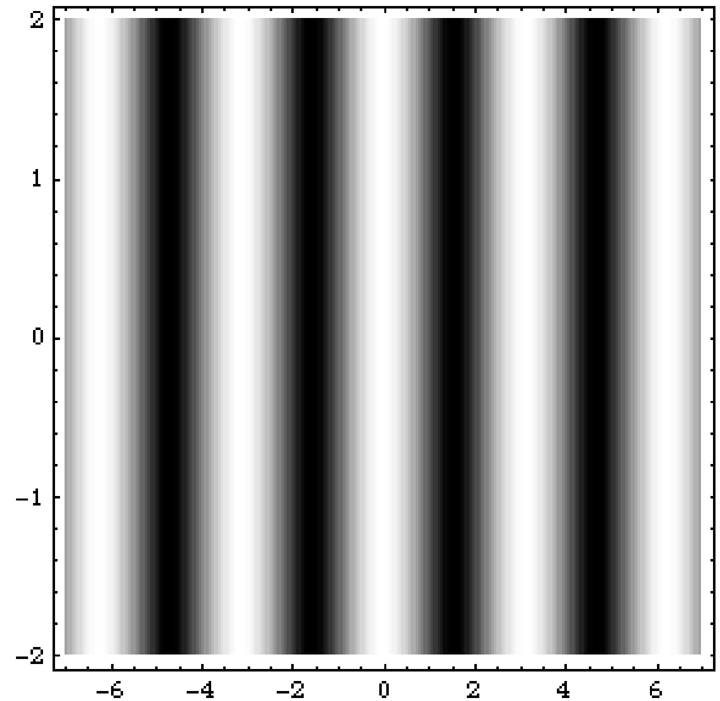
each electron hits the screen as a "particle", detected in a particular location

but the spatial density of events reveals modulations from wave interference

each electron is prepared in exactly the same state (i.e. monochromatic)
then travels through the interferometer
and is then detected (lands) in a spot chosen at random from the distribution of possible positions



$|\Psi(x)|^2$

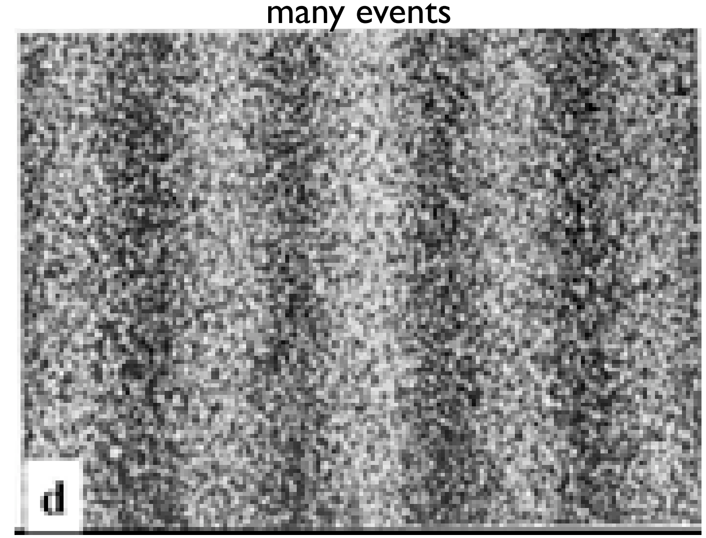


$|\Psi(x,y)|^2$

2-D distribution of possible positions

few events

many events



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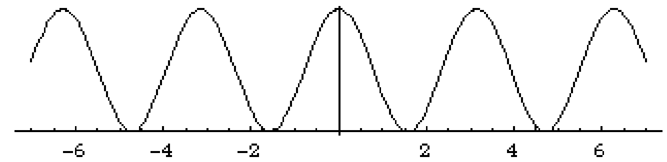

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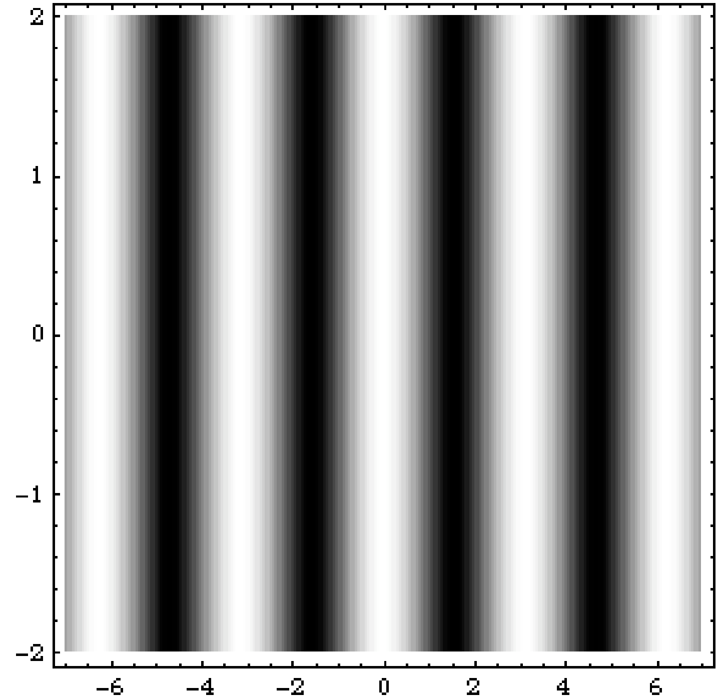

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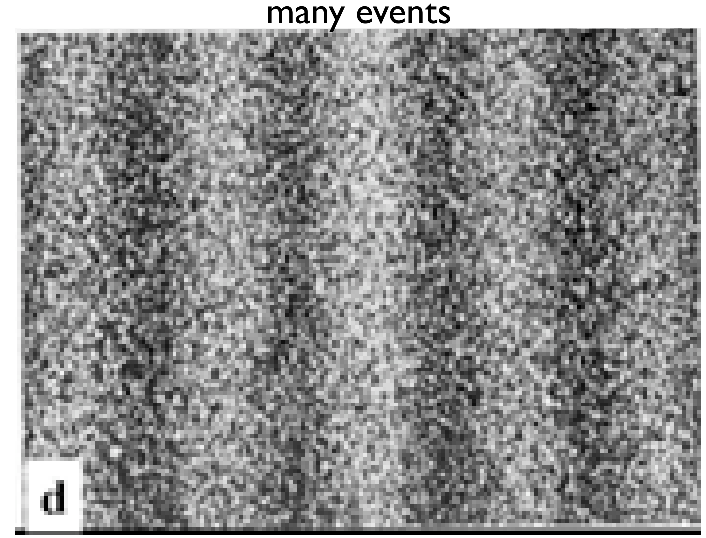

who chooses? *God doesn't play dice with the universe...*

who chooses? ***God doesn't play dice with the universe...***

how do we interpret this indeterminacy?

who chooses? ***God doesn't play dice with the universe...***

"Quantum mechanics is certainly imposing. But an inner voice tells me that it is not yet the real thing. The theory says a lot, but does not really bring us any closer to the secret of the Old One.

I, at any rate, am convinced that He does not throw dice"

Einstein's letter to Max Born (12 December 1926)

Schools of thought regarding quantum indeterminacy

Suppose a particle is detected at some position C. What's really going on?

Realist (Einstein): The particle was at C, though QM couldn't tell us so. The wave function is missing some additional info (QM is incomplete) that would have told us where it was to be detected - a "hidden variable."

Orthodox / Copenhagen interpretation (Bohr): The particle wasn't really anywhere before the measurement - just potentially in some regions. Measurement forced it to "take a stand", compelled it to assume a definite position. In this case it was at C. Nothing can be said as to why at C.

Agnostic / Positivism (Ernst Mach, Heisenberg):
Refuse to answer. QM is a predictive tool and makes no statement about the actual position of the particle before it is measured and therefore it makes no sense to ask where it is before you measure it. There is no point in describing a physical reality that we cannot perceive. Positivism is a rejection of an absolute reality.

In 1964 John Bell showed that it makes an observable difference whether the particle had a precise (though unknown) position prior to the measurement, or not. Agnosticism is not a viable option. It is an experimental question whether 1 or 2 is correct.

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In 1982 Alain Aspect and others vindicated the orthodox view with experimental observations

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but enough of philosophy, let's get back to the mechanisms at play in the Tonomura experiment

Preparation, evolution, measurement

each particle is prepared in exactly the same state

$$\Psi(x, t = 0)$$

emission

evolution, propagation

propagation

the wave function the evolves freely according to the Schroedinger equation

$$\Psi(x, t)$$

and is then detected in a spot chosen at random from the distribution of possible positions

detection
collapse

$$\left|\Psi(x, t)\right|^2$$

distribution of possible positions

$$\Psi'(x, t)$$

new, localized state