PH253 Lecture 11: photons vs. electrons

de Broglie waves

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Outline

1. Better proof for photons?

2. Double slit experiment

Last time:

1. Compton scattering: e^--photon scattering
2. Light behaved like particles ...
3. ...so long as $hf \sim m_{e^-}c^2$, or $\lambda \sim \lambda_c$
4. Implications for measuring position on small scales - uncertainty
5. Next: better proof for photons?
6. Next: why should e^- and photons behave differently?

Open problems according to Einstein, ca. 1905[1]

1. why does the appearance of a photochemical reaction depends only on the color of light, and not on its intensity?
2. why is short wavelength radiation generally more active chemically than long wavelength radiation?
3. why is the kinetic energy of cathode rays (electrons) produced by the photoelectric effect independant on the light intensity?
4. energy given to a light particle when it is emitted is not spread out in infinite space, but remains available for an elementary absorption process
5. i.e., light remains in "bundles"

All explained by photon model!

[1] Adapted from P. Grangier, Séminare Poincaré **2**, 1-26 (2005)

Outline

Single photon scattering

1. Why not use a single photon source?
2. Coherent beam of individual, well-separated photons
3. Atom emits 2 photons of 2 frequencies a few ns apart
4. First one triggers detector to measure second one
5. Second one goes through a beam splitter
6. Which way does it go, or does it split?

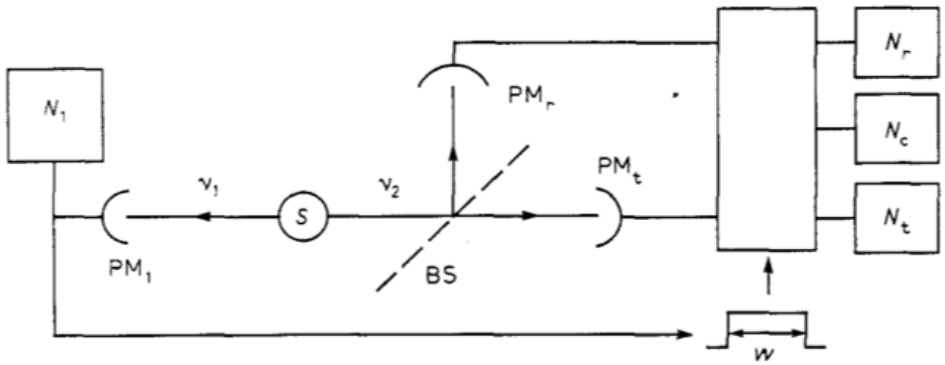


Figure: P. Grangier *et al*, Europhysics Letters **1**, 173 (1986)

Single photon scattering

1. Source S ejects pairs of photons.
2. First ν_1 triggers measurement, counts how many emitted (N_1)
3. Second photon ν_2 encounters beam splitter BS
4. First photon triggering ensures timing is good
5. Wave: both paths (coincident detection, N_c).
6. Particle: has to take one or the other (N_r or N_t)
7. Particle: never see both detectors fire at once

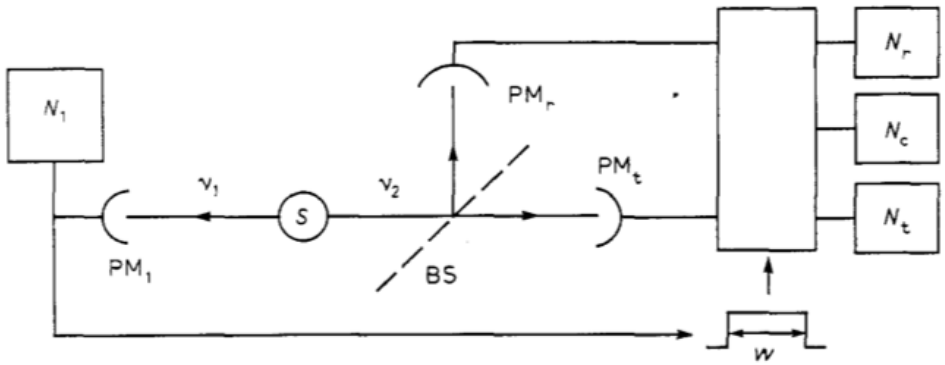


Figure: P. Grangier *et al*, Europhysics Letters **1**, 173 (1986)

Single photon scattering

1. "Anti-bunching": never see simultaneous hits on both detectors
2. Photon can't be split: **either** reflected **or** transmitted, 50/50 chance, never both at once
3. Scan time delay between detectors τ
4. At zero delay (simultaneous detection), intensity $\rightarrow$ zero
5. Light is photons, individual particles!

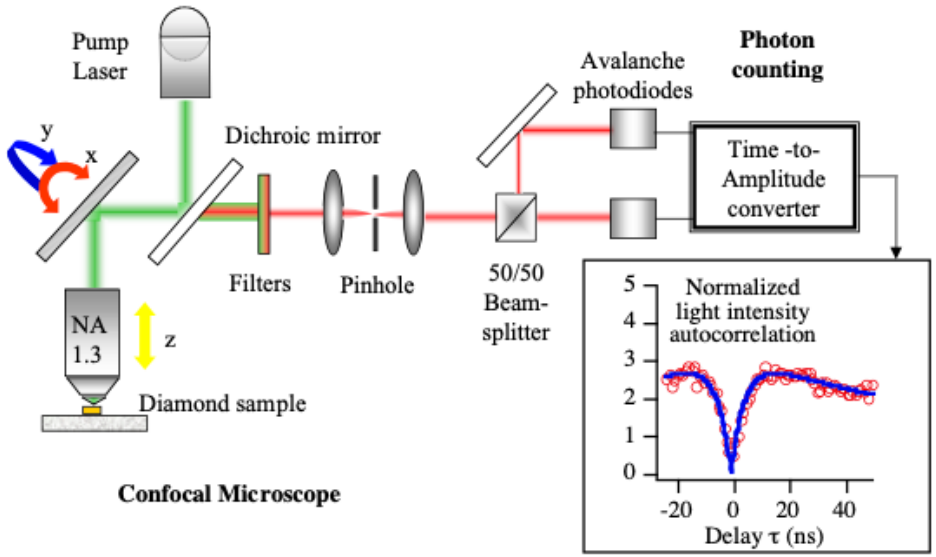


Figure: Modern version. P. Grangier, Séminare Poincaré **2**, 1-26 (2005)

Single photon scattering

1. Interference with single photons? (Mach-Zehnder interferometer)
2. Vary path difference of the two arms = vary phase difference
3. Waves: expect interference. (Broadly similar to double slit)
4. One detector sees constructive, other destructive interference
5. If particles, same for either - 50/50 chance

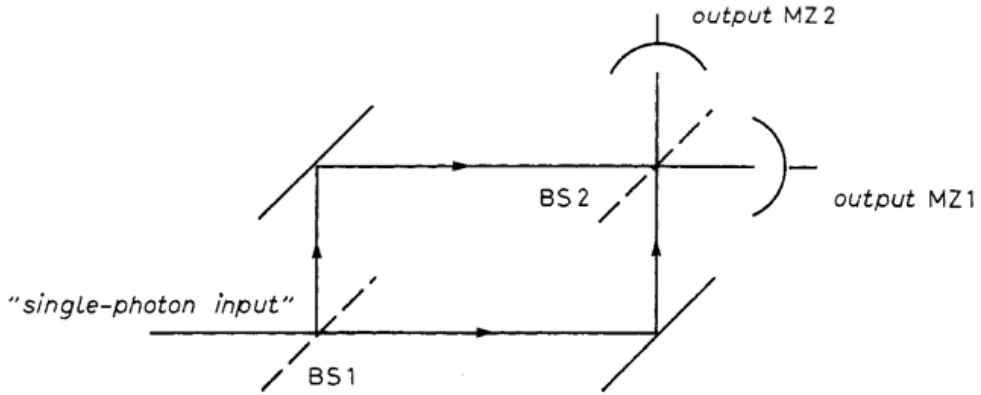
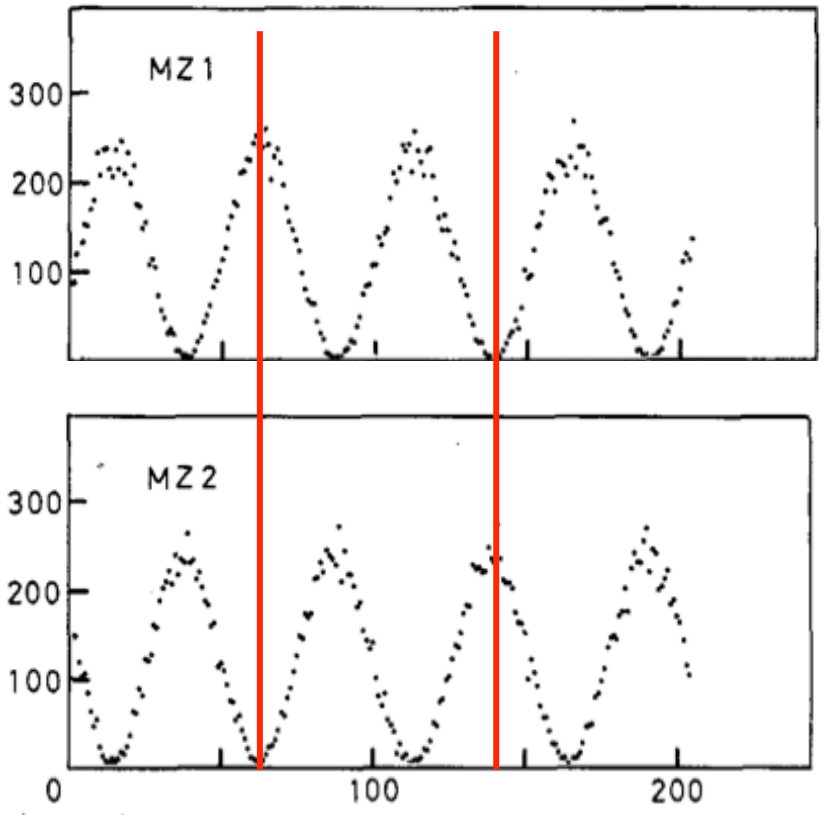


Figure: P. Grangier *et al*, Europhysics Letters **1**, 173 (1986)

Single photon scattering

1. Observe: one is low when the other is high!
2. Exactly what one expects for waves!
3. Light *does* split?!?
4. Clearly light is neither particle nor wave exactly



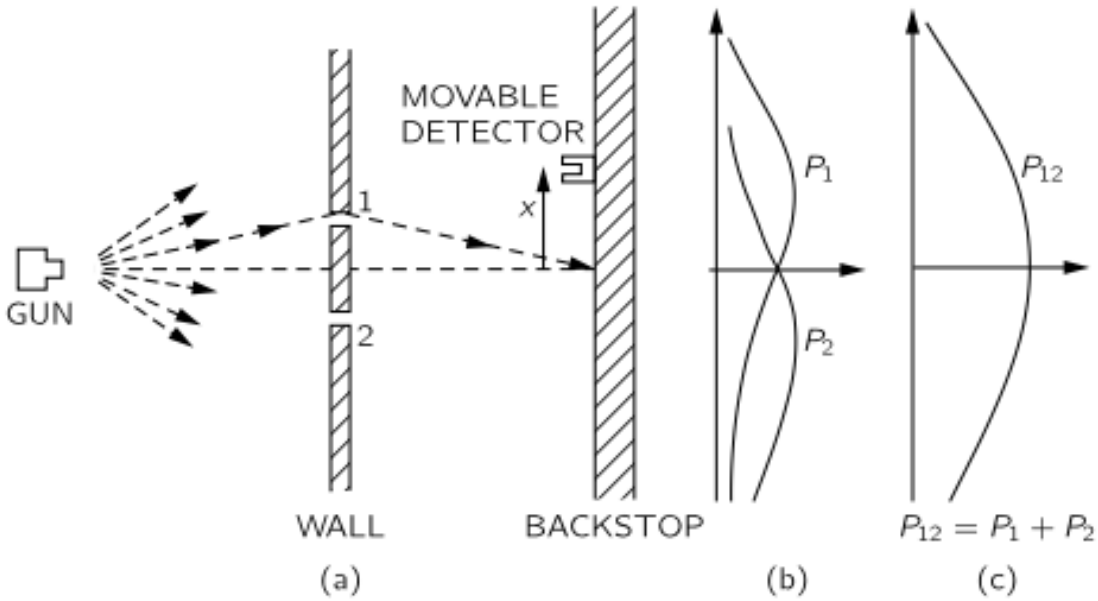
Outline

Back to the drawing board?

1. No, we just need to be more careful and open-minded
2. Look at interference for particles and waves separately
3. Contrast results for photon, e^- with wave/particle
4. Should electrons and photons be different?

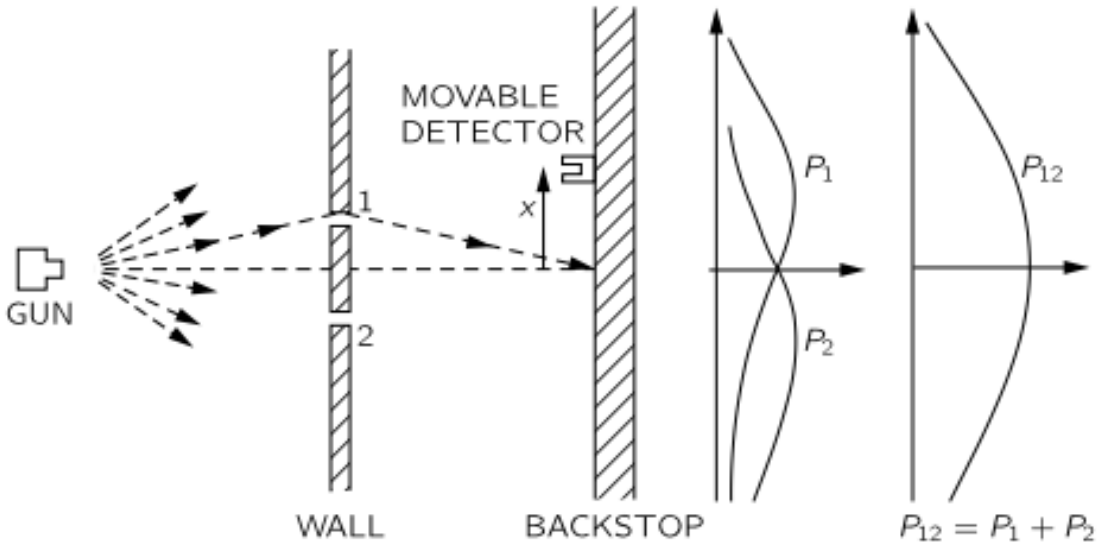
An experiment with particles

1. Gun sprays particles randomly, large spread
2. Shoot at wall with two particle-sized holes
3. Detect hits on far wall. Probability one hits at x?
4. Has to be probability - can't say for certain
5. May bounce off slit, large angular spread
6. Presume constant rate of fire
7. Particles all identical, can't split in two



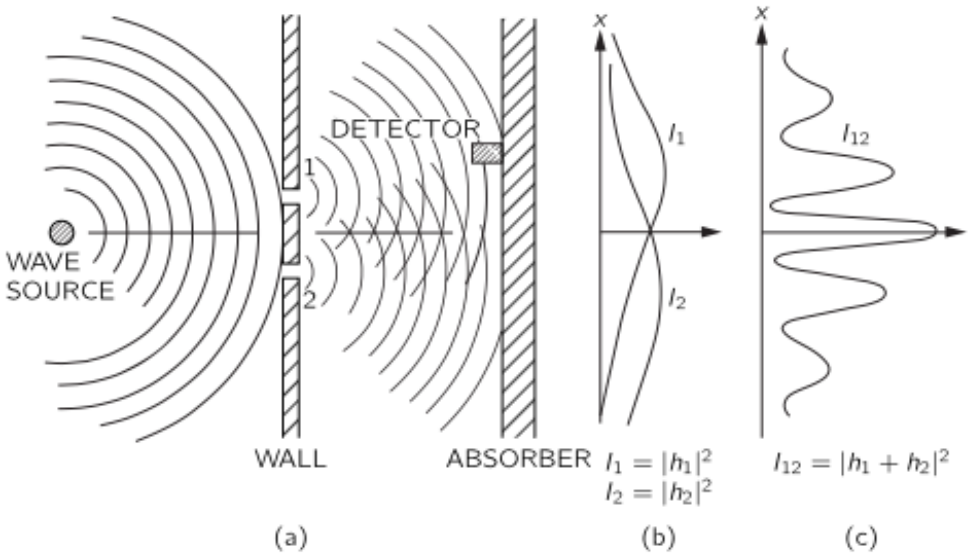
An experiment with particles

1. What does pattern look like?
2. P_1=prob. particle came through slit 1 with slit 2 blocked
3. P_2=prob. particle came through slit 2 with slit 1 blocked
4. P_{12}=prob. through either with *both* open at same time
5. If we collect at the screen with both open, only P_{12} is meaningful
6. Close hole 2, get P_1; close 1, get P_2
7. Both open: clearly $P_{12} = P_1 + P_2$
8. P's add, no interference – clearly particles



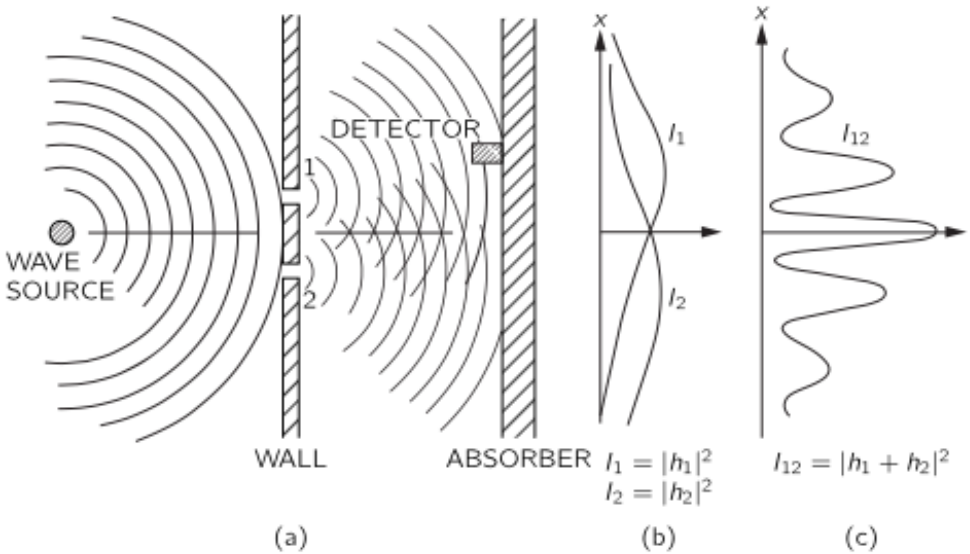
An experiment with waves

1. Try the same with waves!
2. Waves can propagate around holes ...
3. Difference here: intensity on screen can have any value!
4. Not discrete like particles
5. Intensity $\propto$ (amplitude)^2 – height of wave squared
6. $I_1 = |h_1|^2$, $I_2 = |h_2|^2$ with one at a time
7. With both open, $I_{12} = |h_1 + h_2|^2$
8. Meaning: $I_{12} \neq I_1 + I_2$!



An experiment with waves

1. I_{12} depends on relative phases of waves at any point!
2. Can write wave as a complex exponential:
3. $h_1(t) = h_1 e^{i\omega t}$, $h_2(t) = h_2 e^{i(\omega t+\delta)}$
4. $\delta =$ phase difference based on path difference to screen
5. Energy at detector $\sim |h_i|^2$ for one slit i open
6. Both holes open?
7. $h_{\text{tot}}(t) = e^{i\omega t}\left(h_1 + h_2 e^{i\delta}\right)$
8. Energy $\propto |h_{\text{tot}}(t)|^2 = |h_1|^2 + |h_2|^2 + 2|h_1||h_2|\cos\delta$



An experiment with waves

1. Or, $I_{12} = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\delta$
2. Sum of intensities *plus interference term*
3. Since waves take any height, interference shows up
4. Just what you see with water waves.
5. What about photons, or electrons?

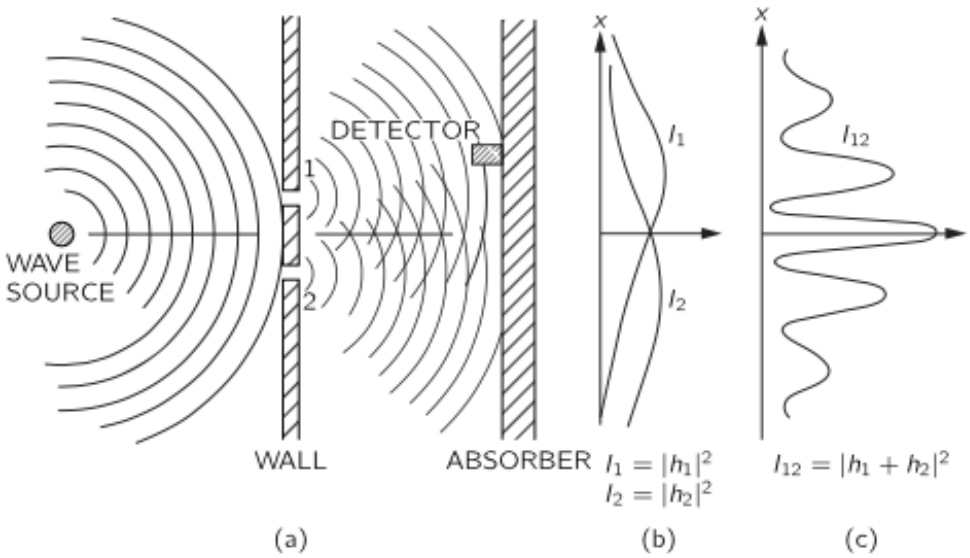


Figure: `https://www.feynmanlectures.caltech.edu/III_01.html`

An experiment with electrons or photons

1. How about photons or electrons?
2. Both behave the same way!
3. But: see both wave and particle aspects
4. Depends on the details ...
5. Probability of going through a single slit is the square of a complex number
6. $P_1 = |\varphi_1|^2$, $P_2 = |\varphi_2|^2$, so $P_{12} = |\varphi_1 + \varphi_2|^2$

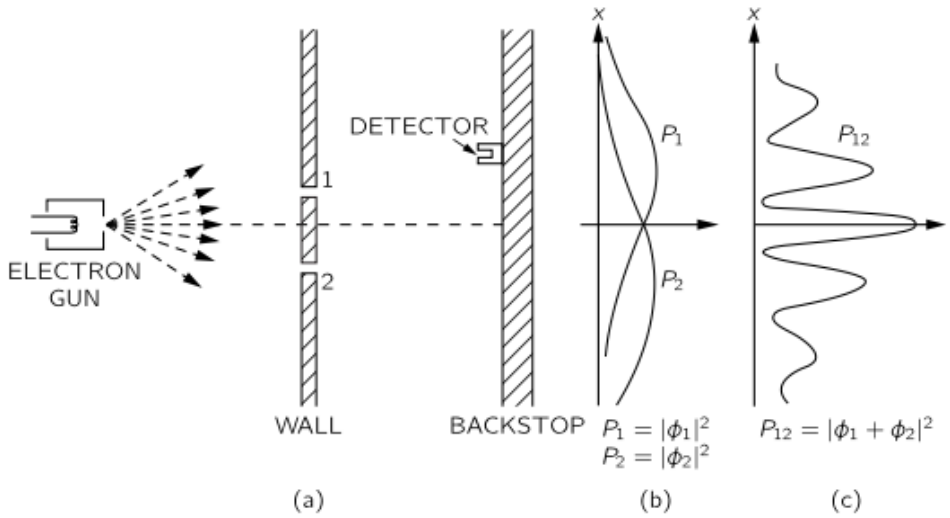


Figure: https://www.feynmanlectures.caltech.edu/III_01.html

An experiment with electrons or photons

1. Detector "clicks" when e^- hits.
2. Only hear full clicks - no "half clicks"
3. Discrete events. Rate erratic, but well-defined average
4. All clicks have same intensity = all events same
5. Try 2 detectors at once? Only one fires at a time
6. Like previous experiment - come through as clumps of definite size, like particles

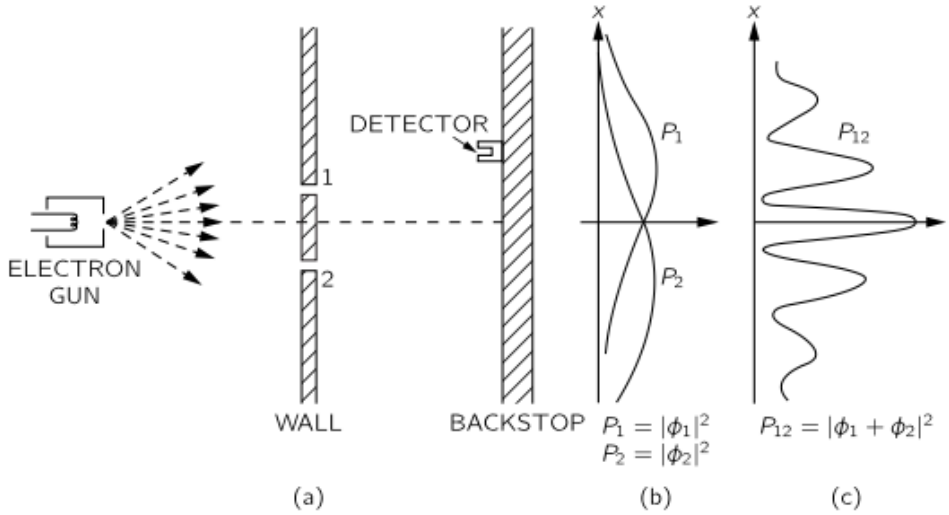


Figure: https://www.feynmanlectures.caltech.edu/III_01.html

An experiment with electrons or photons

1. Electrons & photons clearly discrete, like particles
2. But interference is clearly observed!
3. Probability an e^- or photon hits detector at x?
4. **Proposition 1**: each e^- or photon goes through hole 1 or hole 2, not both
5. Is it true? Has to be for particles.

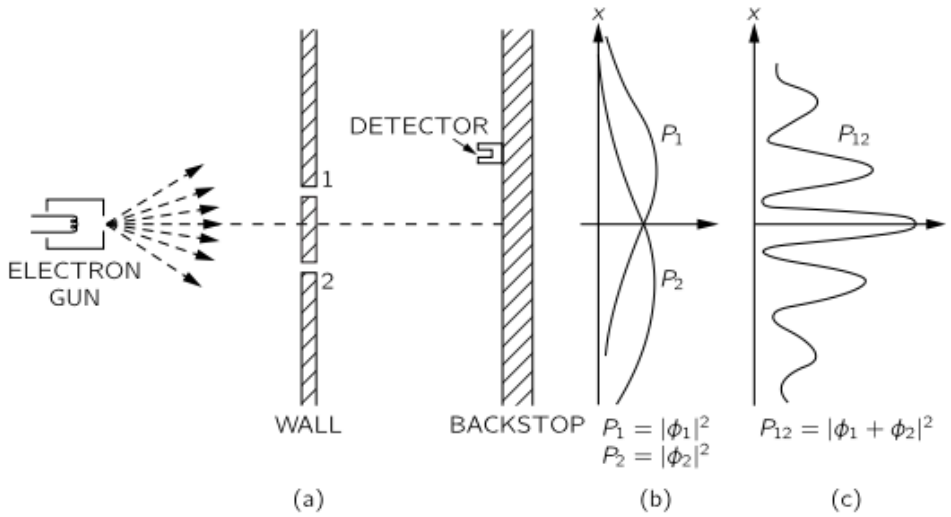
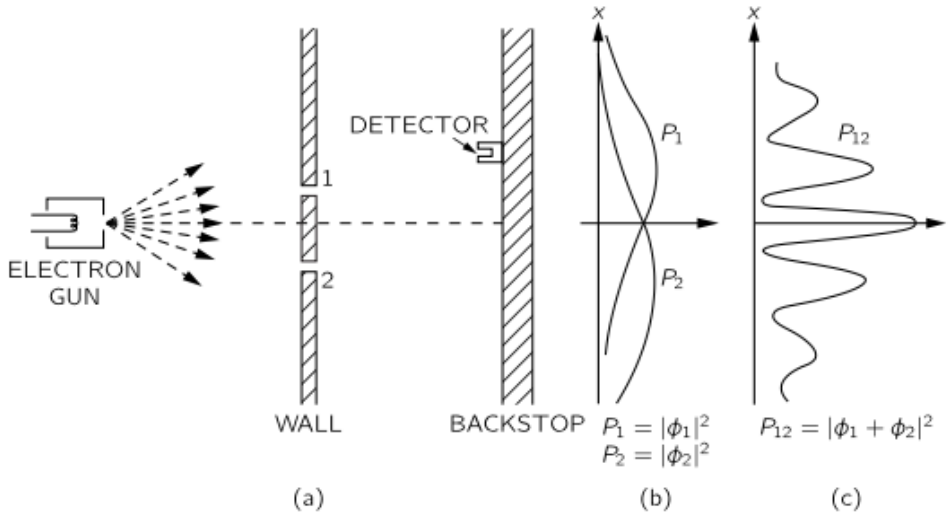


Figure: `https://www.feynmanlectures.caltech.edu/III_01.html`

An experiment with electrons or photons

1. If true, two types of particles:
2. Those going through hole 1, those going through hole 2
3. If so, observed curve must match superposition of single slit results
4. Close 1, measure P_2, close 2, measure P_1
5. Both P_1 & P_2 look like particle result
6. But when *both* slits open? Interference like waves!
7. $P_{12} \neq P_1 + P_2$ like waves!



An experiment with electrons or photons

1. How can this be true?
2. Complex paths back & forth?
3. No - some spots have *higher* intensity with both open!
4. Split in half? No - only full "clicks" heard
5. Worse: at center, $P_{12} > P_1 + P_2$
6. As if closing one hole *decreased* intensity through other!

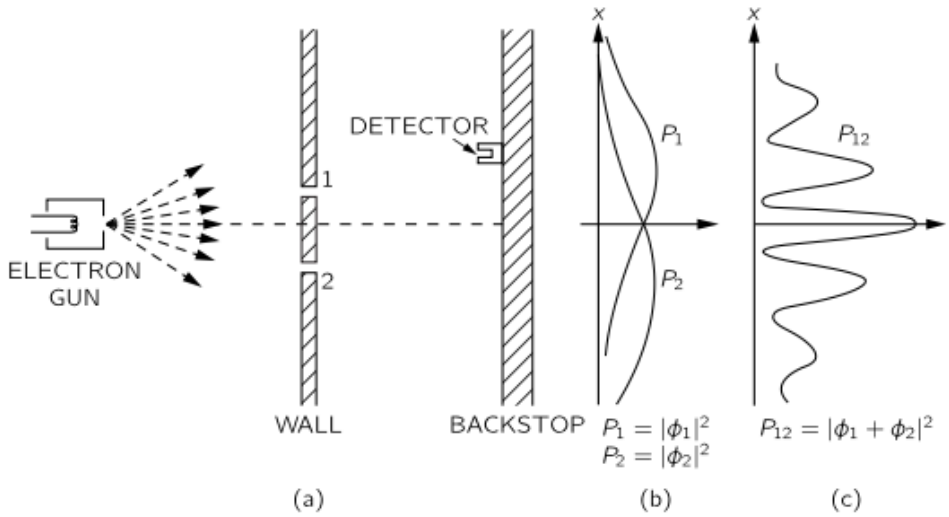


Figure: `https://www.feynmanlectures.caltech.edu/III_01.html`

An experiment with electrons or photons

1. More mysterious as you look closer
2. Math is like water waves. Amplitude for each slit ϕ_i
3. $P_1 = |\varphi_1|^2$, $P_2 = |\varphi_2|^2$, so $P_{12} = |\varphi_1 + \varphi_2|^2$
4. Conclusion: e^- or photons arrive in lumps, like particles
5. But, probability of arriving is like wave interference
6. Proposition 1 is false: not true that e^- or photon takes only 1 hole a particle, it takes both like a wave!

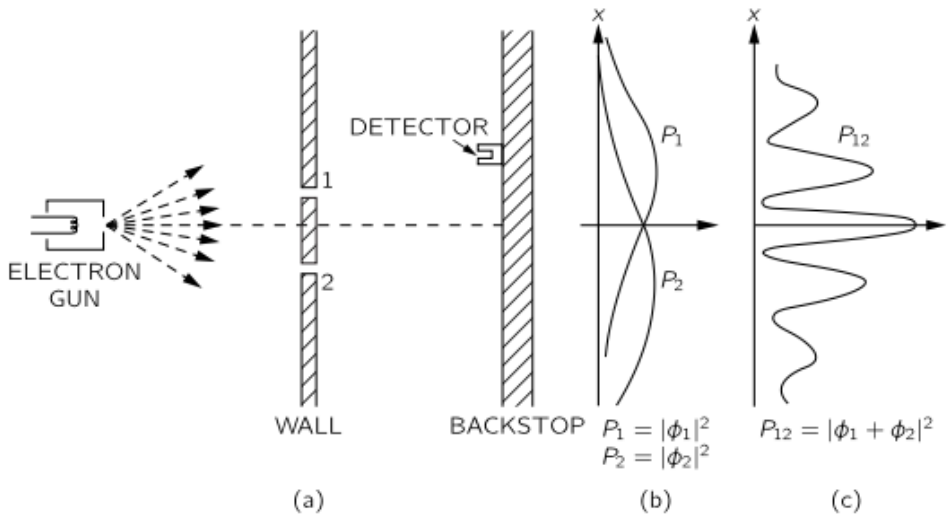
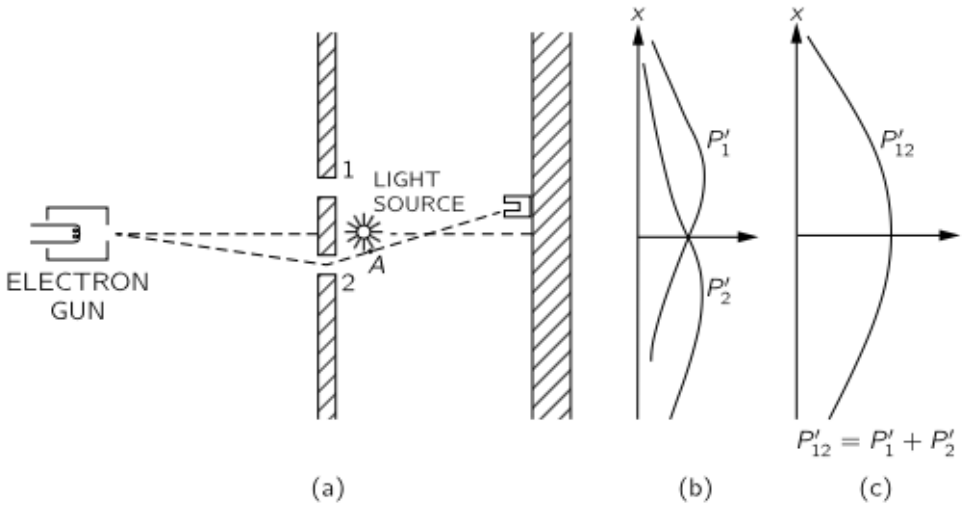


Figure: https://www.feynmanlectures.caltech.edu/III_01.html

Watching the particles

1. Let's watch the e^- - light source near one slit
2. If e^- takes this slit, scatters photon to detector
3. Every time detector clicks, see photon from 1 or 2, not both
4. Proposition 1 now true? P_1 & P_2 look like particles
5. No! Interference is gone when we watch it!
6. Problem: photon disturbs e^-, altered experiment by looking



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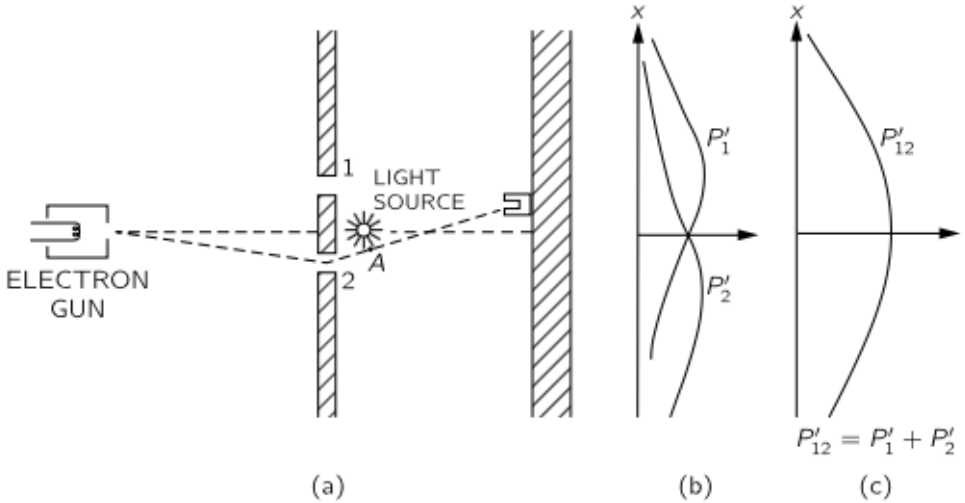
Watching the particles

1. e^- gains p, E from photon. Destroys interference
2. Less bright? No - photon energy independent of intensity
3. Too dim, not enough photons . . . some e^- sneak by undisturbed
4. Interference starts to come back when too dim!
5. Less momentum of photon, more gentle? No - $p = h/\lambda$
6. Low p means large λ, and can't resolve!
7. λ big enough to not disturb, can't resolve slits individually



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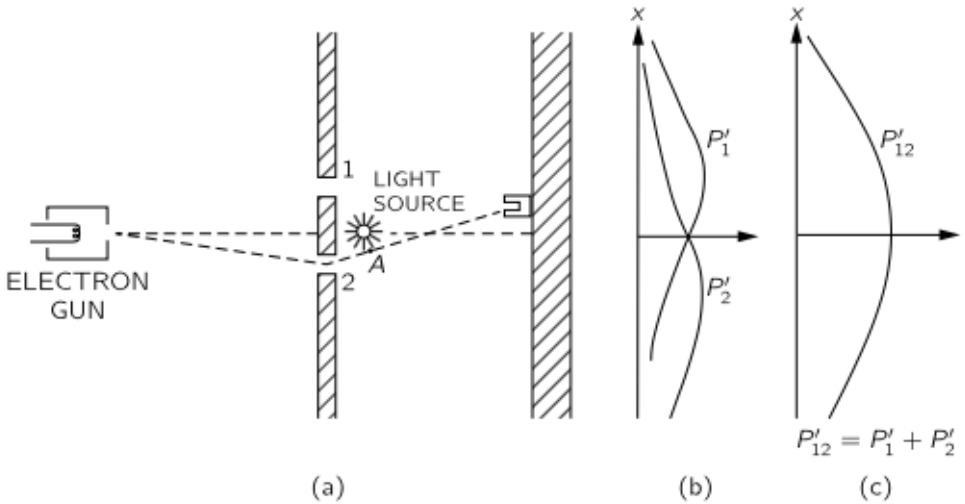
Watching the particles

General principle: can't design an apparatus to tell which hole the particle went through without disturbing it enough to destroy interference.

1. Can't measure without altering result
2. Particle takes both slits and interferes if we don't watch
3. Look close enough to tell: goes through 1 or 2
4. Idea: de Broglie's hypothesis
5. All matter is wave-like on a small enough scale
6. What is the scale?



Summary of double slit experiment

1. Probability of an event in an ideal experiment is the square of a complex number φ
2. $P = |\varphi|^2, \phi =$ amplitude
3. When an event can happen in several alternate ways, add amplitudes separately
4. $\varphi_{\text{total}} = \varphi_1 + \varphi_2$, $P_{\text{total}} = |\varphi_1 + \varphi_2|^2 \neq P_1 + P_2$ – interference

Summary of double slit experiment

1. If an experiment is capable of determining which alternative is actually taken, add probabilities
2. $P_{\text{total}} = P_1 + P_2$ – no interference, independent events
3. Implication: can only work with probabilities most of the time
4. Question: how are e^- also wave-like? (de Broglie)
5. Light originally waves, now particles.
6. e^- originally particles now waves.
7. Dogs & cats living together, mass hysteria.
8. This is real. Let's watch.
   `https://www.youtube.com/watch?v=mypzz99_MrM&t=7m12s`