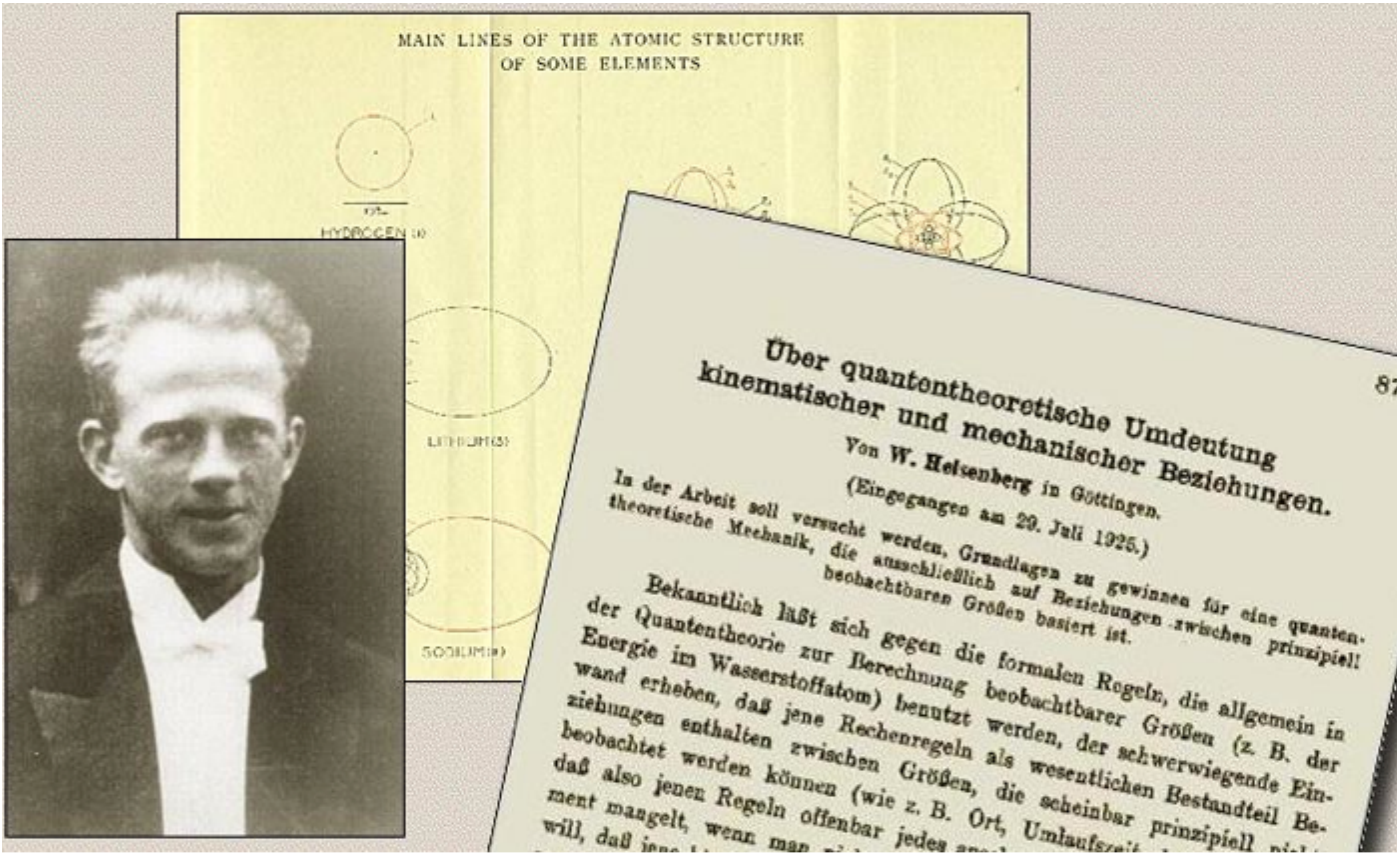
Heisenberg: The Uncertainty Principle



Determinism of Classical Mechanics

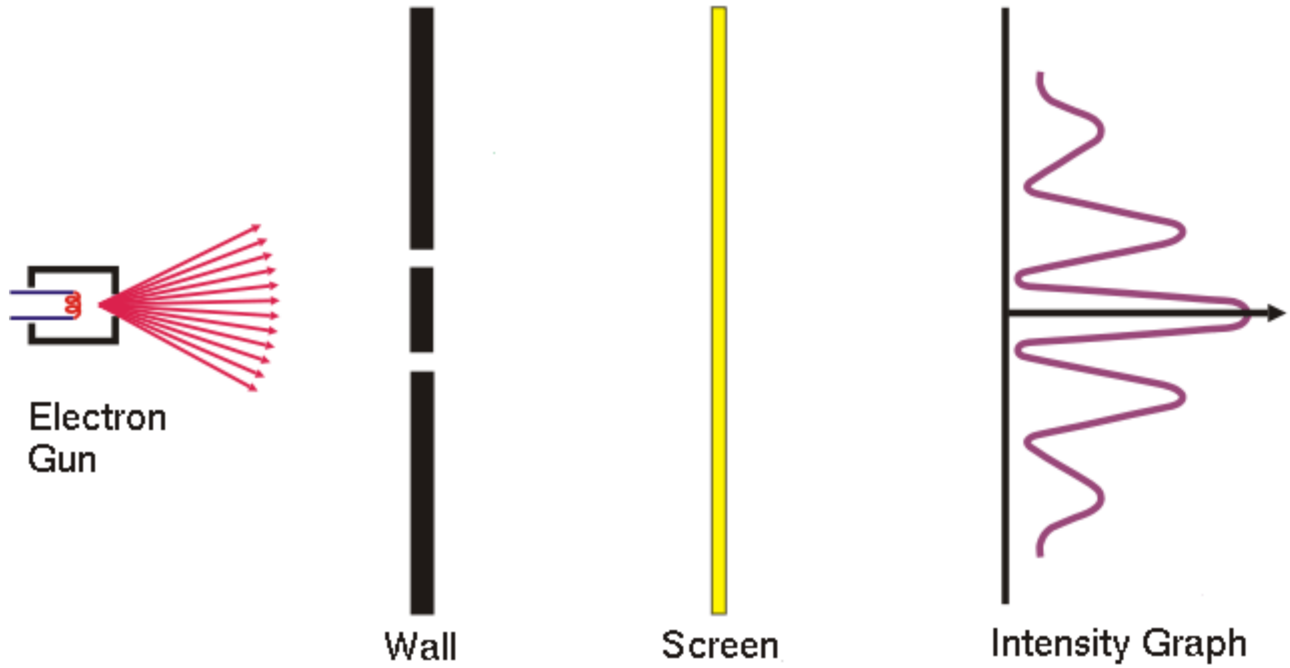
- Suppose the positions and speeds of all particles in the universe are measured to sufficient accuracy at a particular instant in time

- It is possible to predict the motions of every particle at any time in the future (or in the past for that matter)

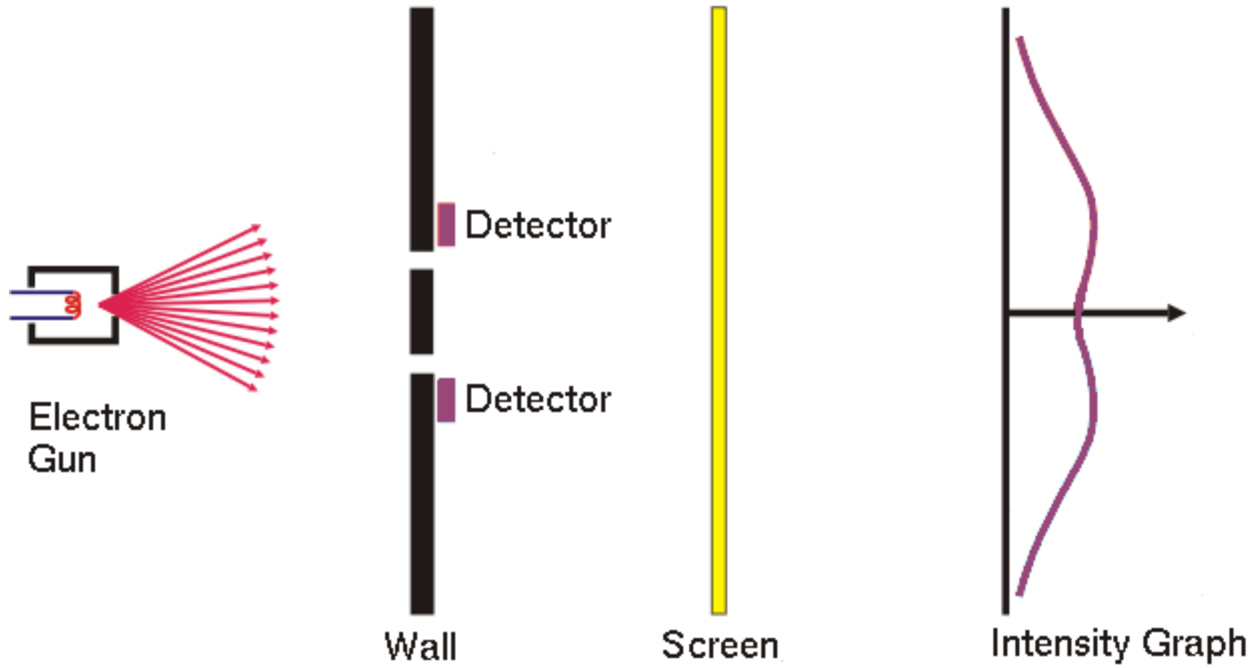
Role of an Observer

- The observer is objective and passive
- Physical events happen independently of whether there is an observer or not (objective reality)

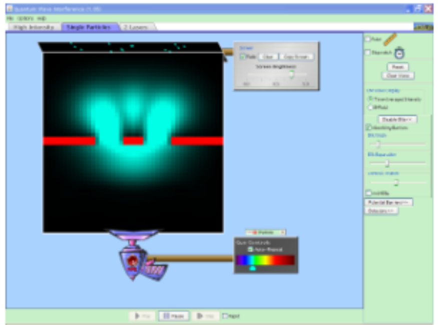
Double-Slit Experiment:
cannot predict where electron would land



Double-Slit Experiment:
act of observation affects behavior of electron



Interactive simulations:
http://phet.colorado.edu/en/simulation/quantum-wave-interference



Role of an Observer in Quantum Mechanics

- The observer is *not* objective and passive
- The act of observation changes the physical system irrevocably (subjective reality)

Werner Heisenberg:

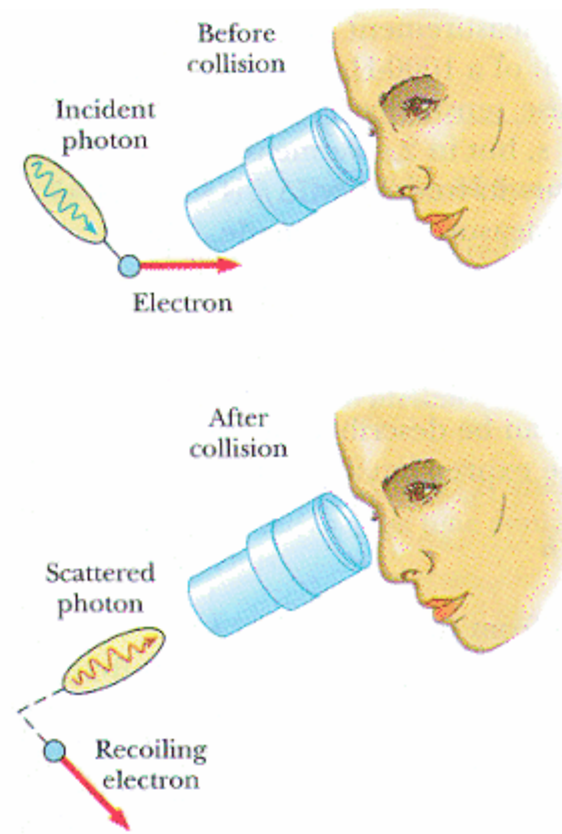
- In the world of very small particles, one cannot measure any property of a particle without interacting with it in some way
- This introduces an unavoidable uncertainty into the result
- One can never measure all the properties exactly

Measuring the position and momentum of an electron

- Shine light on electron and detect reflected light using a microscope

- Minimum uncertainty in position is given by the wavelength of the light

- So to determine the position accurately, it is necessary to use light with a short wavelength



Measuring the position and momentum of an electron

- By Planck's law $E = hc/\lambda$, a photon with a short wavelength has a large energy
- Thus, it would impart a large 'kick' to the electron
- But to determine its momentum accurately, electron must only be given a small kick
- This means using light of long wavelength

Fundamental Trade Off …

- Use light with short wavelength:

  accurate measurement of position but not momentum
- Use light with long wavelength:

  accurate measurement of momentum but not position

Heisenberg's Uncertainty Principle (1 dimension)

- The more accurately you know the position (i.e., the smaller Δx is) , the less accurately you know the momentum (i.e., the larger Δp is); and vice versa
- It is impossible to know *both* the position and momentum exactly, i.e., $\Delta x=0$ and $\Delta p=0$

uncertainty in momentum

$$\Delta x \, \Delta p \geq \frac{h}{4\pi}$$

uncertainty in position

Note: 1) the uncertainties Δx and Δp are inherent in the physical world and have nothing to do with the skill of the observer

2) h very small, these uncertainties are not observable in everyday life

Heisenberg's Uncertainty Principle - Energy and Time

$$\Delta E \, \Delta t \geq \frac{h}{4\pi}$$

- The more accurately we know the energy of a body, the less accurately we know how long it possessed that energy

- The energy can be known with perfect precision ($\Delta E = 0$), only if the measurement is made over an infinite period of time ($\Delta t = \infty$)

Summary: Lessons from Heisenberg

- The idea of a perfectly predictable universe cannot be true
- There is no such thing as an ideal, objective observer
- However nature offers probabilities which can be calculated and tested