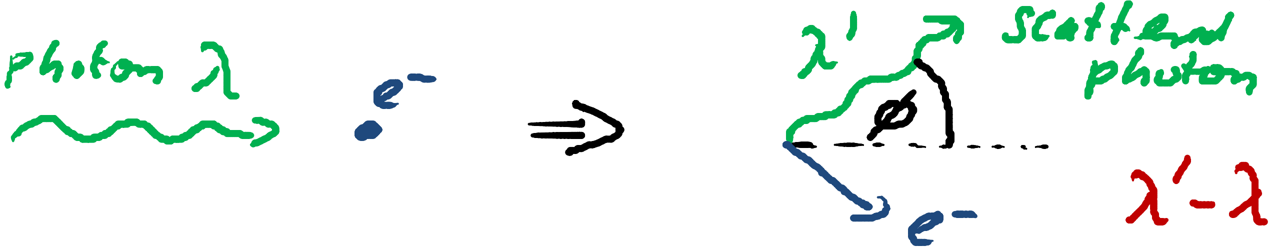
Recap I

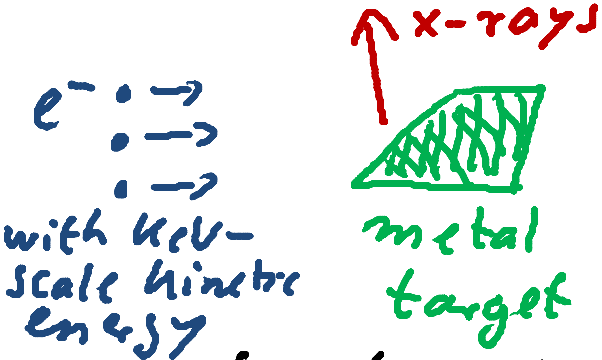
Lecture 38

- Evidence of Photons: Compton Effect



$$\lambda' - \lambda = \Delta\lambda = \frac{h}{m_e c}(1-\cos\phi)$$

- X-Ray Production:

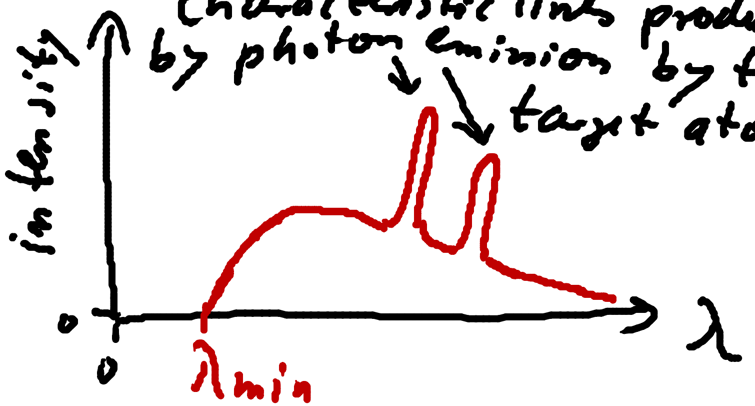


with keV-scale kinetic energy

electrons interact with target atoms and may lose part of their kinetic energy by generating an x-ray photon

⇒ continuous spectrum

$$\lambda \geq \frac{hc}{K_0} = \lambda_{min}$$



characteristic lines produced by photon emission by the target atoms

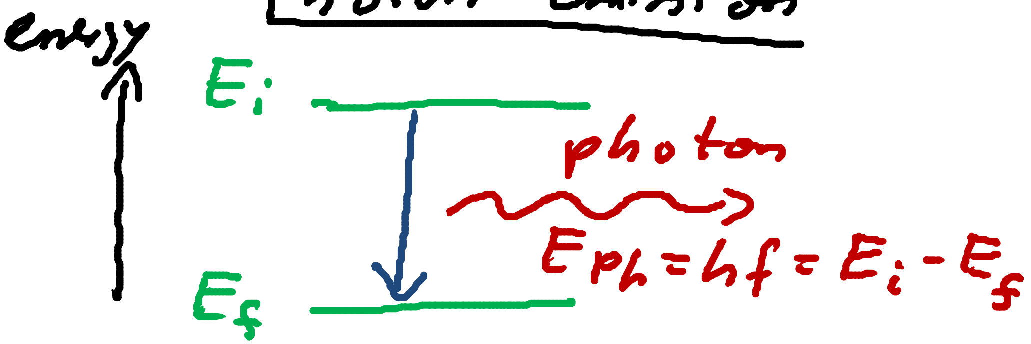
Recap II

- **The quantized Atom:**

Radiation emitted by independent atoms shows sharp spectral lines

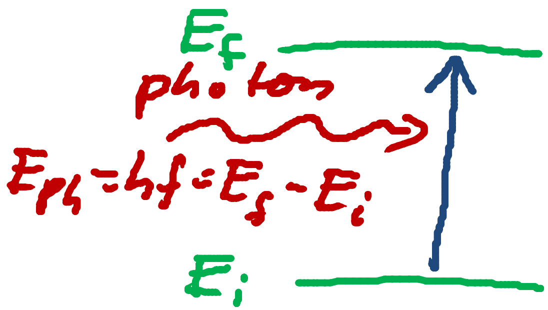
$\Rightarrow$ Atoms exist in states of discrete quantized internal energy!

Photon Emission



$$E_{ph} = hf = E_i - E_f$$

Photon Absorption



$$E_{ph} = hf = E_f - E_i$$

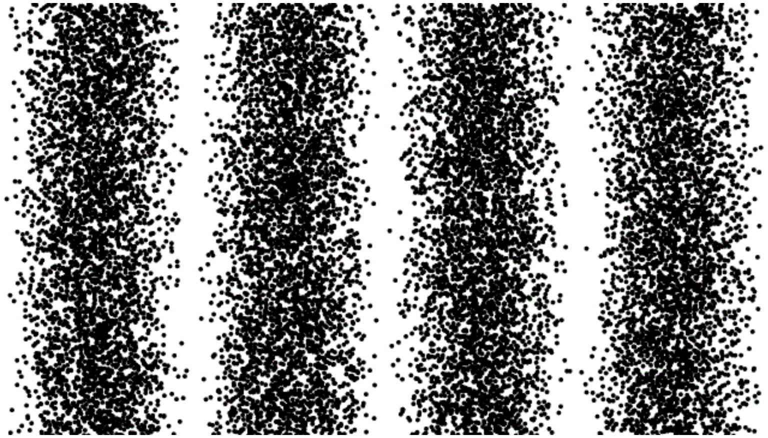
- Hydrogen Atom:

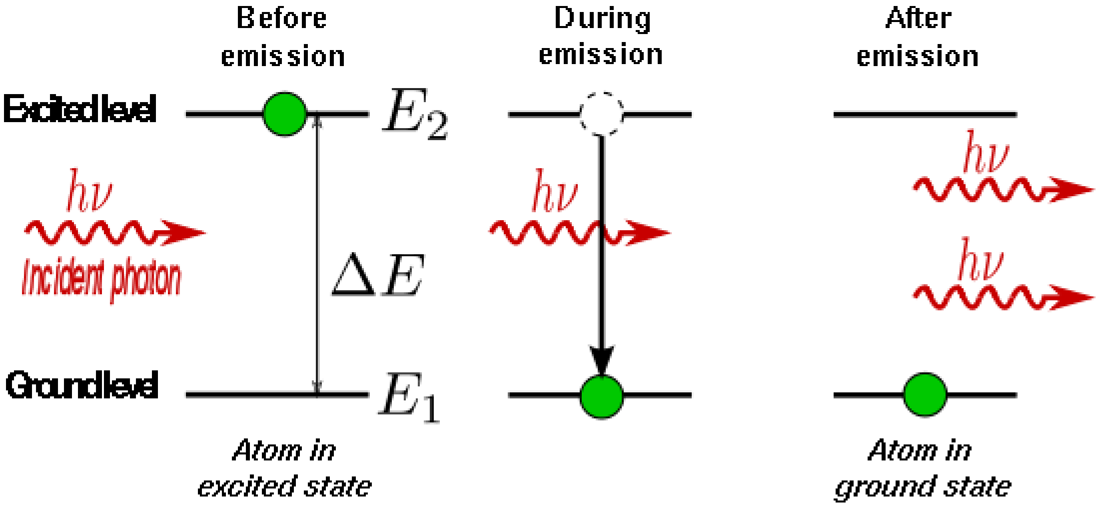
total kinetic and potential energy of proton and electron in H-atom $\rightarrow$

$$\boxed{E_n = -13.6\,\text{eV}\,\frac{1}{n^2}} \qquad n = 1, 2, 3, \ldots$$

Today:

- **Lasers**
  - **Stimulated photon emission**
- **Particle waves**

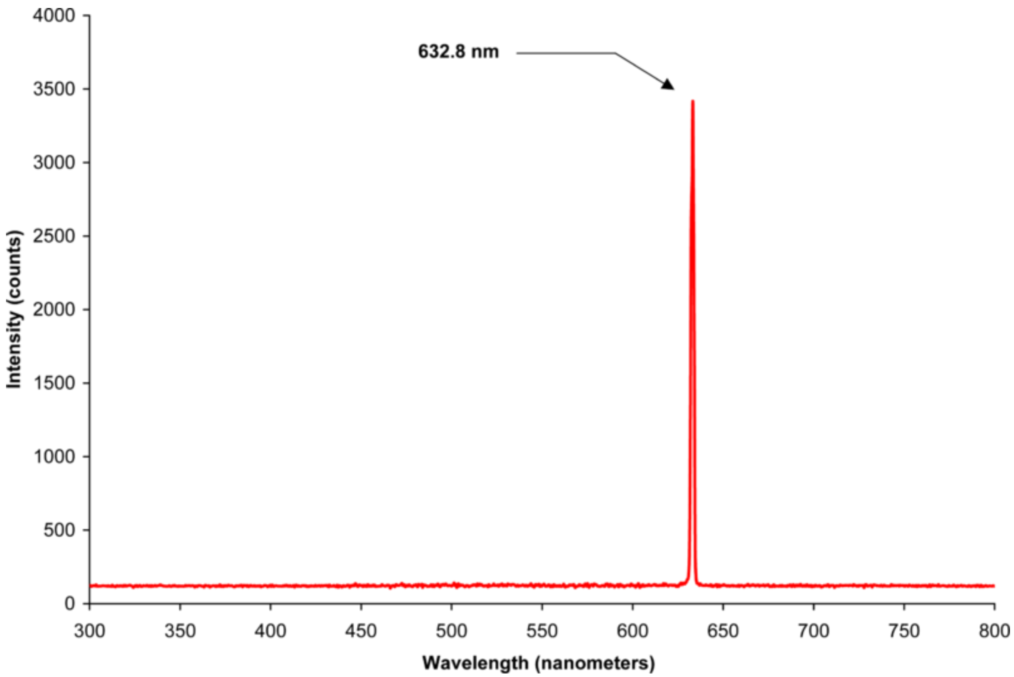




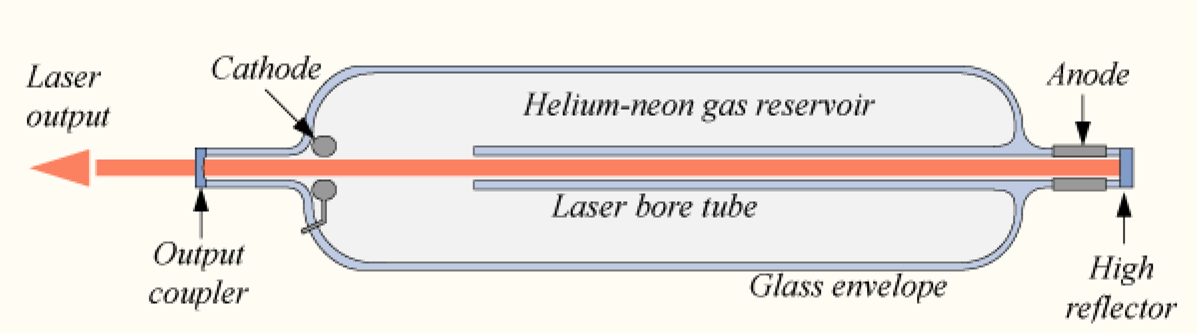
$$E_2 - E_1 = \Delta E = h\nu$$

LASER

Light
Amplification by
Stimulated
Emission of
Radiation



Example: He-Ne Laser (red):



99% reflective mirror

optical oscillator

100% reflective mirror

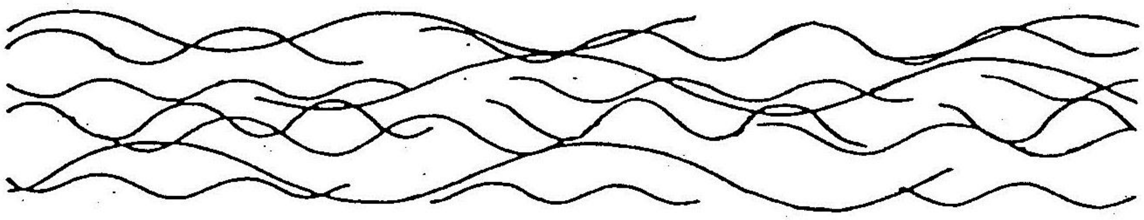
Special characteristics of laser light:

1. Highly **monochromatic** (single wavelength).
2. Highly **coherent**. Individual long waves (wave trains) for laser light can be several hundred km long. The corresponding coherence length for wave trains emitted by a light bulb is typically less than a meter.
3. Highly **directional**. Spreading of the beam is due to diffraction at the exit aperture of the laser.
4. Can be **sharply focused**. Intensity of 10^{17} W/cm^2 can be readily obtained. (An oxyacetylene flame only has an intensity of about 10^3 W/cm^2.)

Coherent vs. Incoherent Light

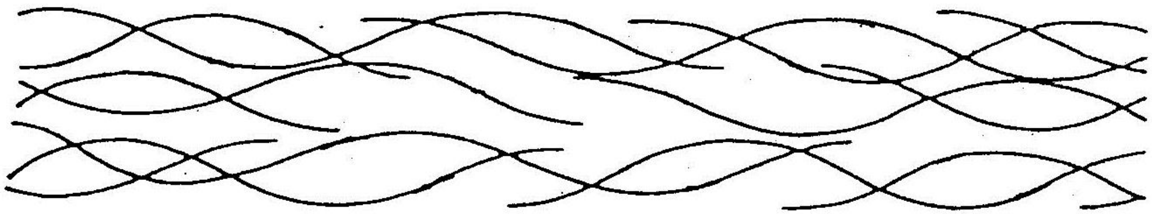
Polychromatic - incoherent

Incoherent white light contains waves of many frequencies (and wavelengths) that are out of phase with one another.



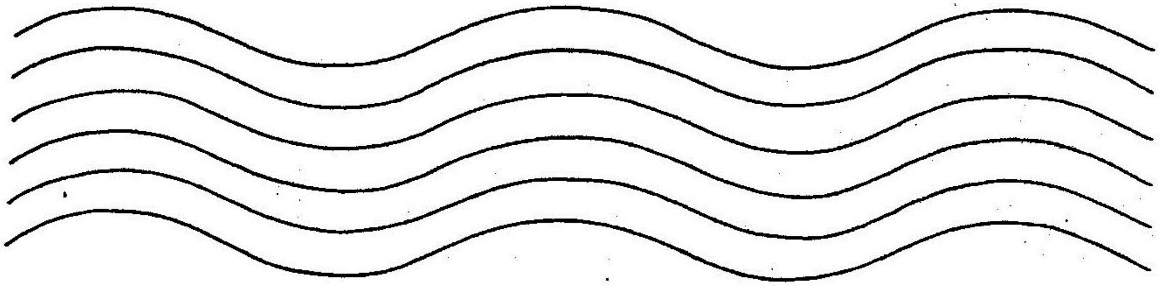
Monochromatic - incoherent

Light of a single frequency and wavelength is still out of phase.



Monochromatic - coherent

Coherent light: all the waves are identical and in phase.

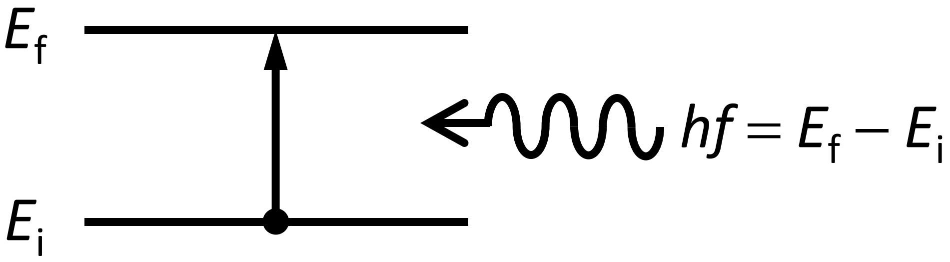


Laser uses:

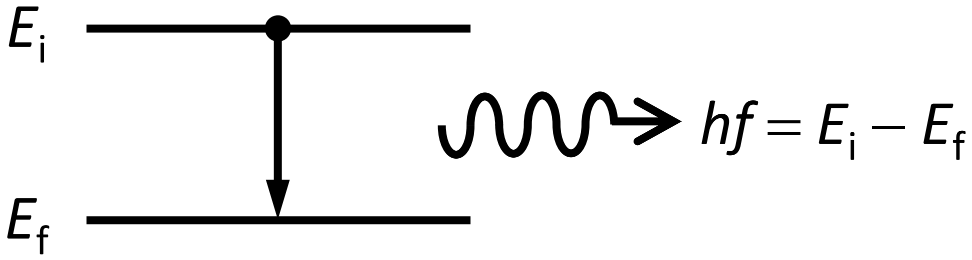
- Voice & data transmission over optical fibers.
- Read & write CDs, DVDs, BDs.
- Read bar codes.
- Laser printing.
- Surgery.
- Welding.
- Cutting metal.
- Cutting cloth.
- Photochemistry.
- Spectroscopy.
- Interferometry.
- Optical trapping.
- Nuclear fusion research.
- Weapons.
- Surveying.
- Range finding.
- Holography.
- Microscopy (e.g., confocal, two-photon).

Laser action depends on three processes:

1. Absorption:



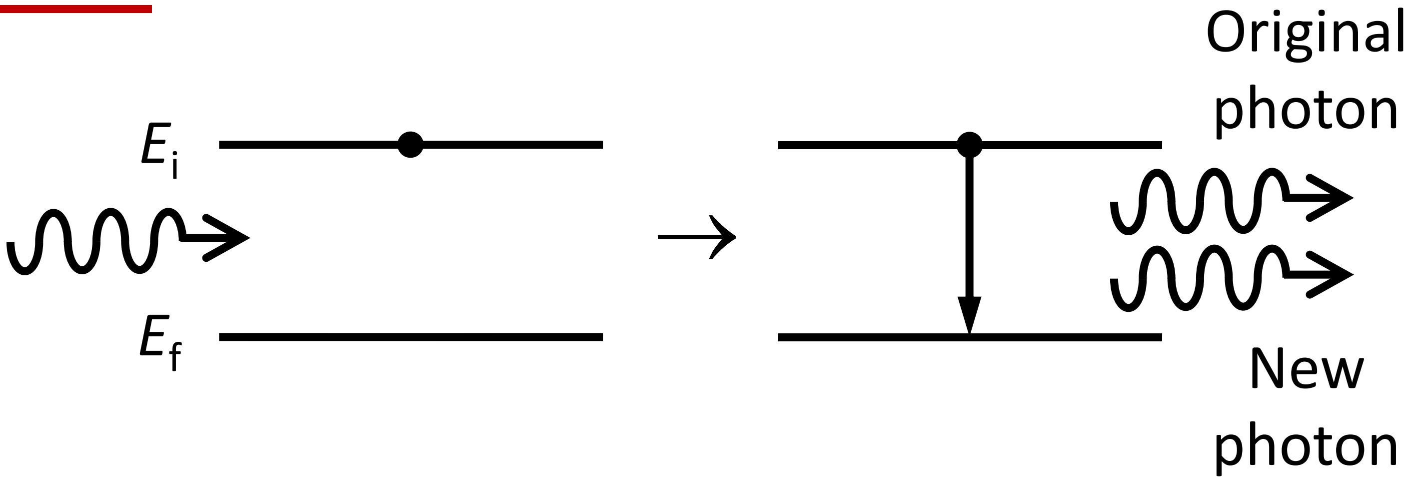
2. Spontaneous emission:



- Emission is not triggered by an outside influence.
- Mean lifetime of excited atoms in ‘normal’ states is $\sim 10^{-8}$ s.
- For metastable excited states this can be 10^5 times longer.

3. Stimulated emission:

$hf = E_\mathrm{i} - E_\mathrm{f}$

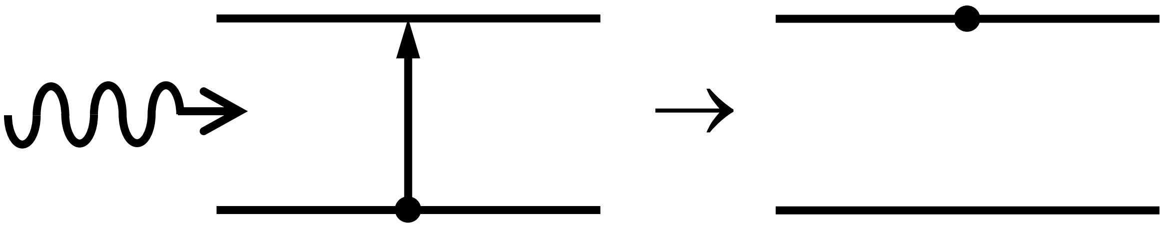


- Original & new photons are identical.
- Associated waves have the same: - energy, (λ)
  - direction
  - phase
  - polarization

- The probability per atom for absorption is the same as the probability per atom for stimulated emission.

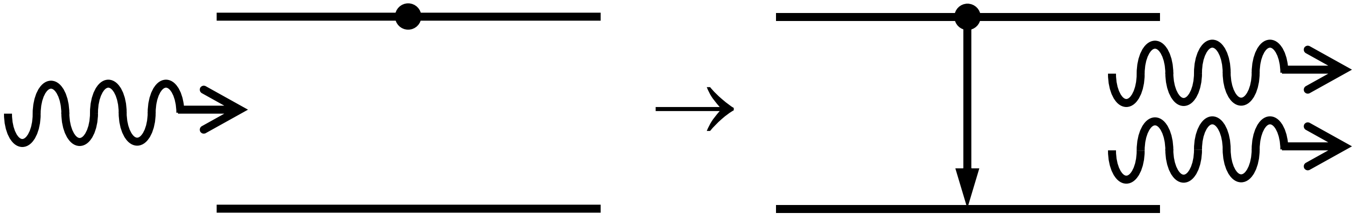
Two competing processes:

Absorption:



No
photons

Stimulated emission:

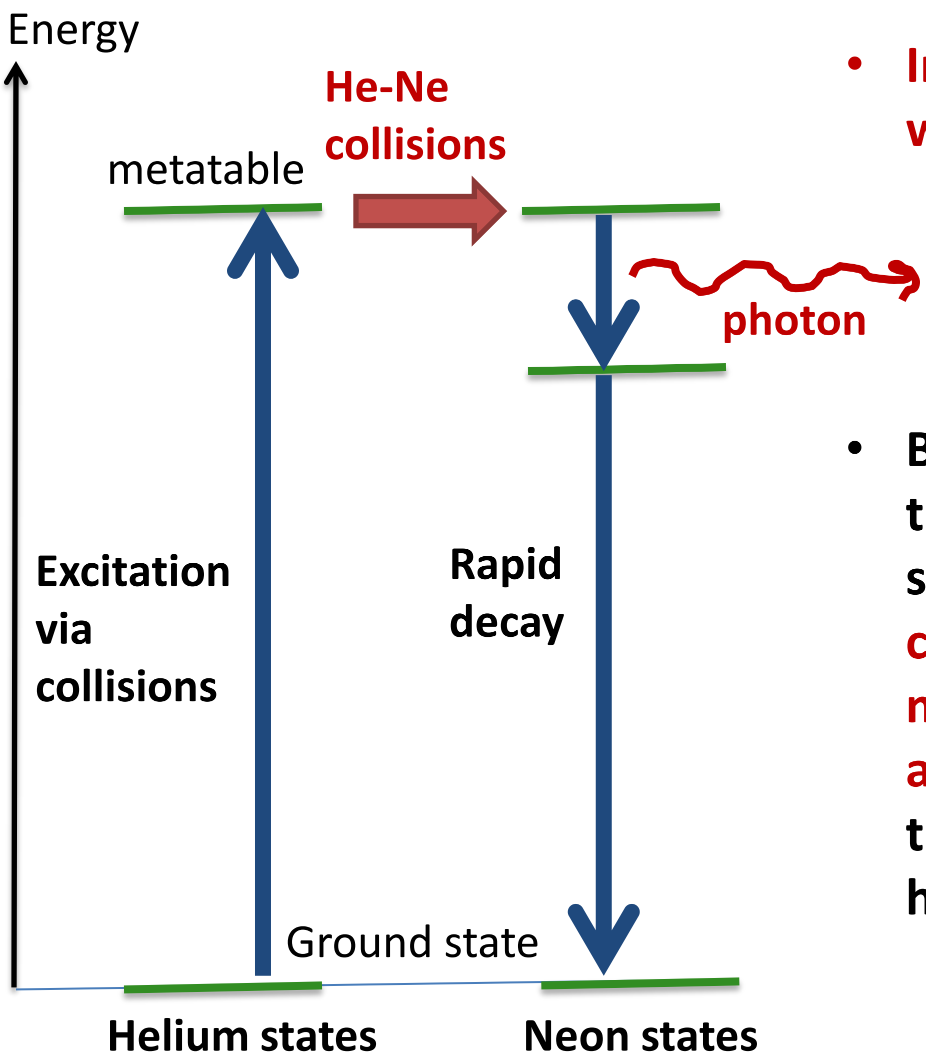


Two
photons

- **For lasing, need more atoms in the higher energy state than in the lower energy state. This condition is called a *population inversion*. It must be artificially created by some input of energy.**

Example: Population Inversion Collisions

Simplified energy level diagram of a He-Ne laser:



Energy

metatable

He-Ne collisions

photon

Excitation via collisions

Rapid decay

Ground state

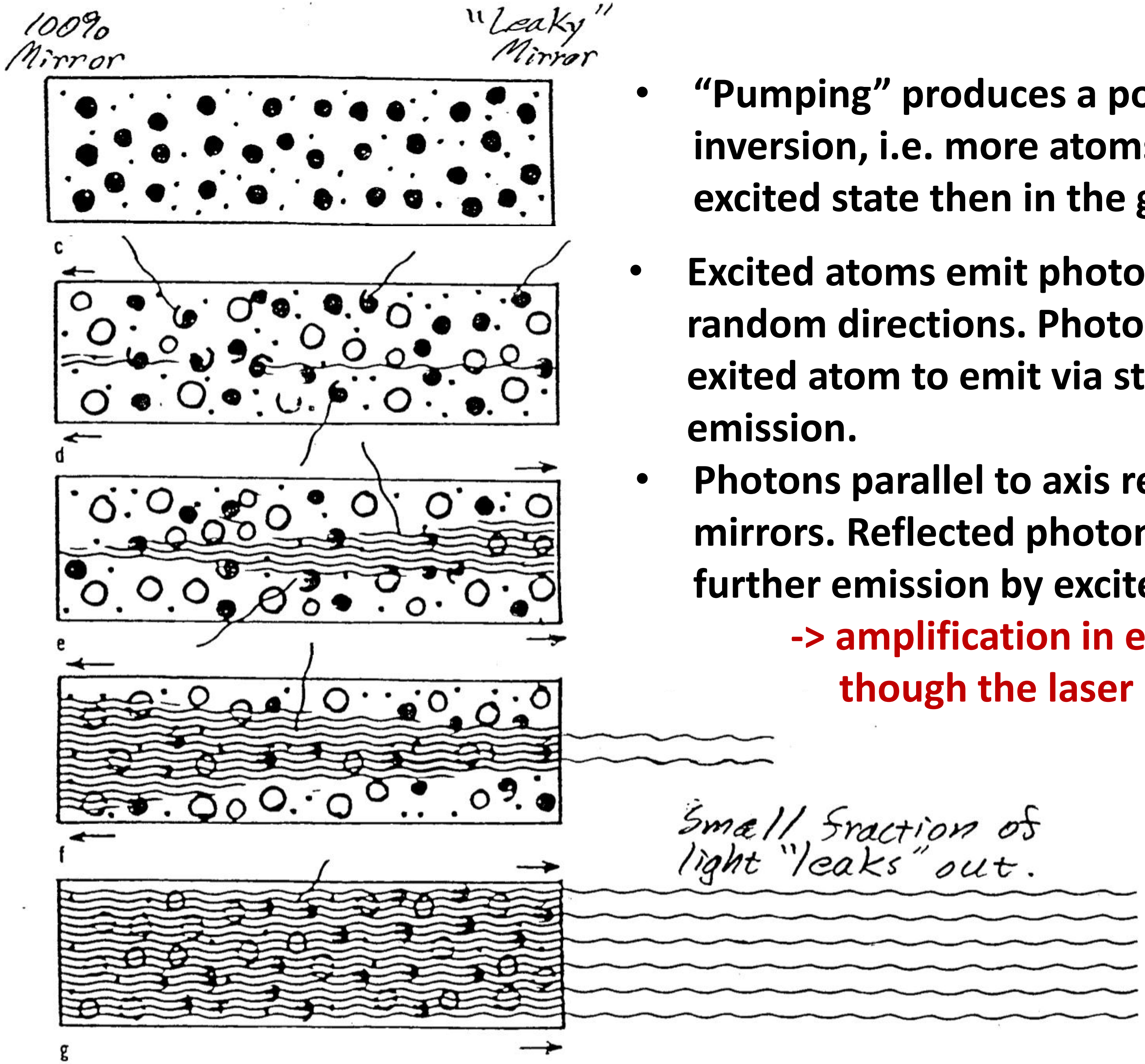
Helium states

Neon states

- **Inelastic collision of energetic electrons with ground state helium atoms**
  - **Collisions excite helium atoms from the ground state to higher energy excited states, among them a along-lived metastable state.**
- **Because of a near coincidence between the energy level of the metastable He state, and an excited state of neon, collisions between these helium metastable atoms and ground state neon atoms results in a selective and efficient transfer of excitation energy from the helium to neon.**

  -> Population inversion for Ne

Startup of a LASER



- "Pumping" produces a population inversion, i.e. more atoms in are in an excited state then in the ground state.
- Excited atoms emit photons; initially in random directions. Photons cause other exited atom to emit via stimulated emission.
- Photons parallel to axis reflect from mirrors. Reflected photons stimulate further emission by excited atoms.

-> amplification in each pass though the laser medium.

Particle (Matter) Waves

- for photons: $\lambda = \frac{h}{p}$
- Louis de Broglie (1924) proposed:

1.) **All** particles have wave-like and particle-like properties, not only photons!

2.) A particle with momentum p has a "**particle wave**" associated with its motion with wavelength:

wavelength: wave-like property

$$\boxed{\lambda = \frac{h}{p}}$$

momentum: particle-like property

⇒ for particle with mass $m>0$:

- Kinetic energy: $\underline{\mathcal{K}} = \frac{1}{2} m v^2 = \frac{1}{2m}(mv)^2 = \underline{\frac{p^2}{2m}}$

$$\Rightarrow \boxed{\lambda = \frac{h}{p} = \frac{h}{\sqrt{2m\mathcal{K}}}}$$

"rest-mass energy"

- According to Einstein: energy-mass relation: $\boxed{E_0 = mc^2}$

(⇒ can convert energy to mass and mass to energy)

$$\Rightarrow \boxed{\lambda = \frac{h}{p} = \frac{h}{\sqrt{2m\mathcal{K}}} = \frac{hc}{\sqrt{2E_0\mathcal{K}}}}$$

⇒ for a photon:

- energy: $E_{ph} = hf = \frac{hc}{\lambda} \Rightarrow \lambda = \frac{hc}{E_{ph}}$
- momentum: $p = \frac{h}{\lambda} = \frac{h}{hc} E_{ph} = \frac{E_{ph}}{c}$

$$\boxed{P_{photon} = \frac{E_{photon}}{c}}$$

$$\boxed{\lambda = \frac{h}{p_{ph}} = \frac{hc}{E_{ph}}}$$

Particle waves $\lambda = h/p$: Order of Magnitude Estimate

Or: Why wasn't this noticed before?

thermal neutrons (300K) $\Rightarrow \lambda = 1.5\,\text{Å}$ } ≈ atom size

electrons at 100 eV $\Rightarrow \lambda = 1.2\,\text{Å}$

neutrons at 10 MeV $\Rightarrow \lambda = 9 \cdot 10^{-15}\,\text{m}$ } size of nucleus

$m = 1\,\text{g}$ at $1\,\text{m/s}$ $\Rightarrow \lambda = 7 \cdot 10^{-31}\,\text{m}$

compare to visible light $\Rightarrow \lambda = 400-700\,\text{nm}$

$= 4$ to $7 \cdot 10^{-7}\,\text{m}$

→ recall 2-slit exp.: maxima for $\sin\theta = \frac{n\lambda}{d} < 1$

need $\lambda \approx d$

$\Rightarrow$ for particle: need "slit" spacing / diffraction grid on Å scale (or less)

$\Rightarrow$ use crystals!

An electron's kinetic energy K is the same as the energy E_{ph} of a photon with 10 nm associated wavelength. How does the electron's de Broglie wavelength compare with the wavelength associated with the photon ($hc = 1240$ eV nm; $E_{0,e-}=511$ keV)?

A. $\lambda_{\text{electron}} > \lambda_{\text{photon}}$.

[✓ B.] $\lambda_{\text{electron}} < \lambda_{\text{photon}}$.

C. $\lambda_{\text{electron}} = \lambda_{\text{photon}}$.

D. Not enough information.

$$\lambda_{ph} = 10\,nm = \frac{hc}{E_{ph}}$$

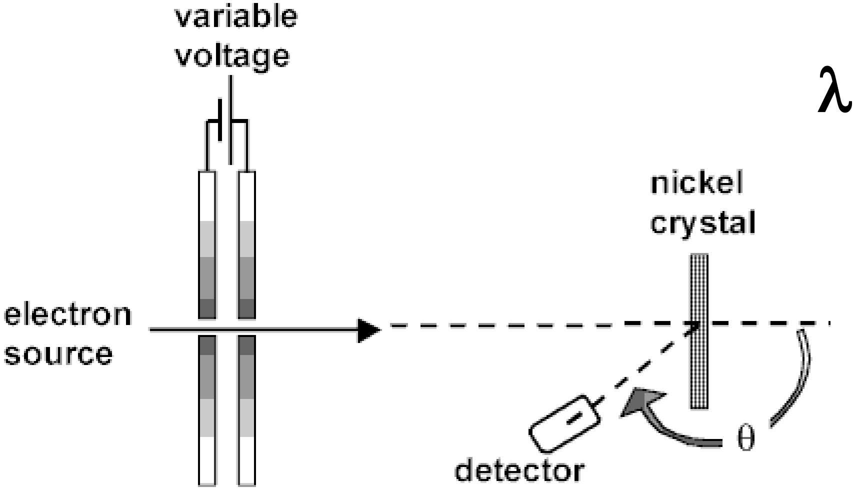
$$\Rightarrow \underline{E_{ph}} = \frac{hc}{\lambda_{ph}} = \frac{1240\,eV\,nm}{10\,nm} = \underline{124\,eV}$$

$$\lambda_{e^-} = \frac{h}{p} = \frac{hc}{\sqrt{2E_0 K}}$$

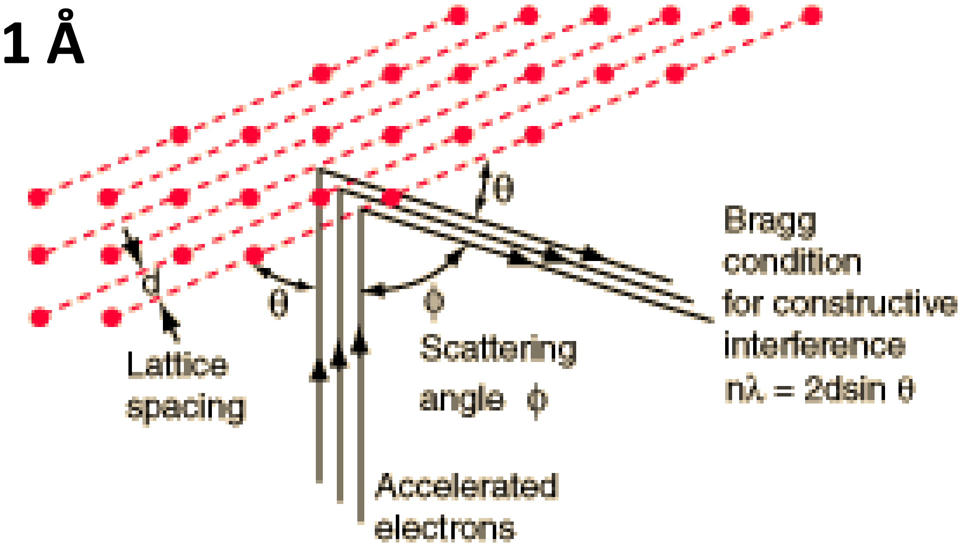
$$= \frac{1240\,eV\,nm}{\sqrt{2\cdot 511\,keV \cdot 124\,eV}} = \underline{\underline{0.1\,nm}}$$

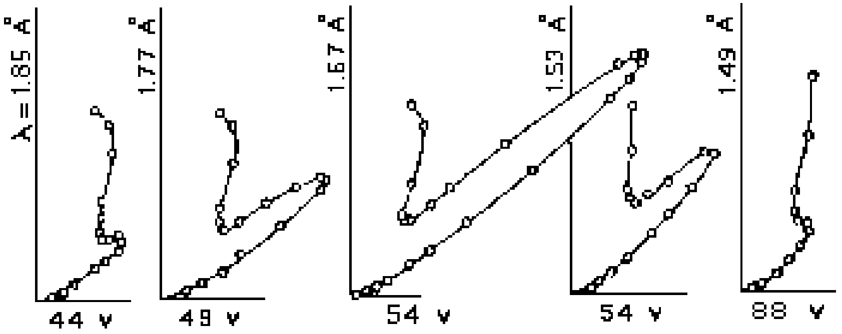
Evidence for de Broglie's Particle Waves:

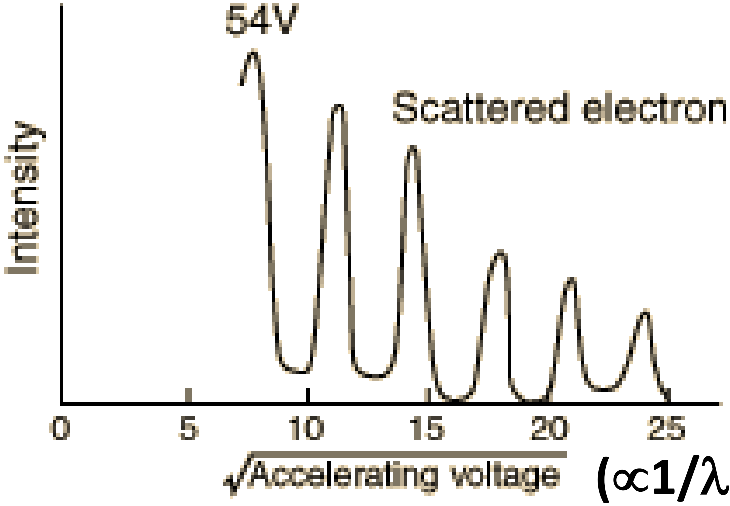
Davisson-Germer Experiment (1925): Scattering of low energy electrons by a crystal surface



$\lambda \approx 1$ Å



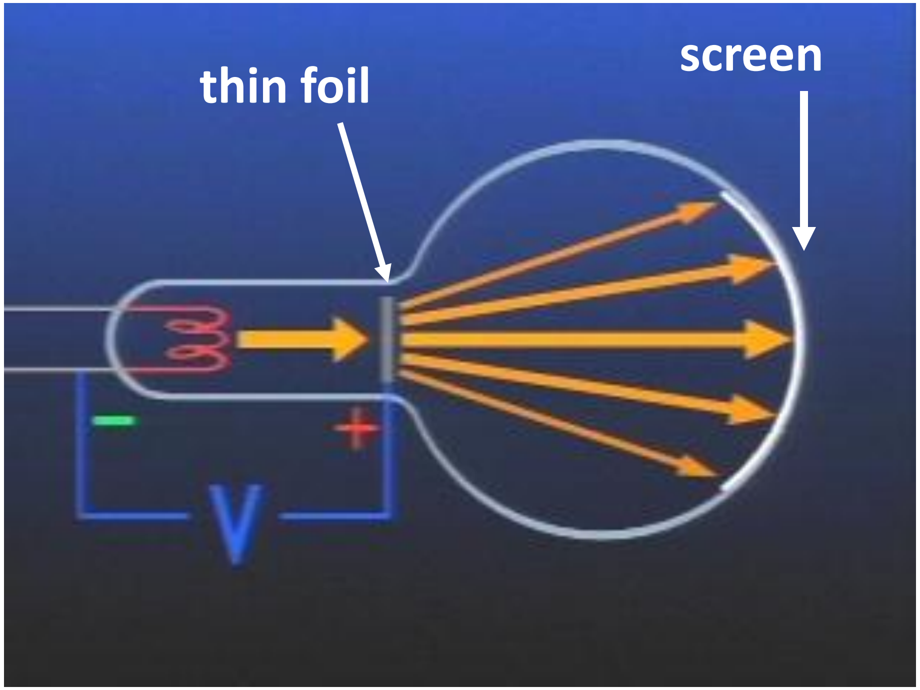


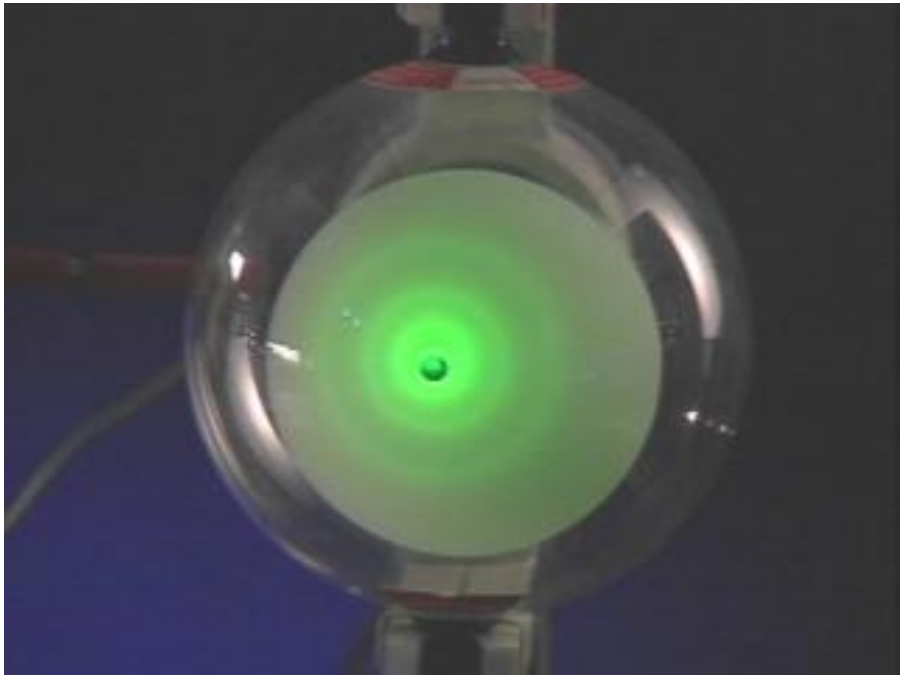


($\propto 1/\lambda$)

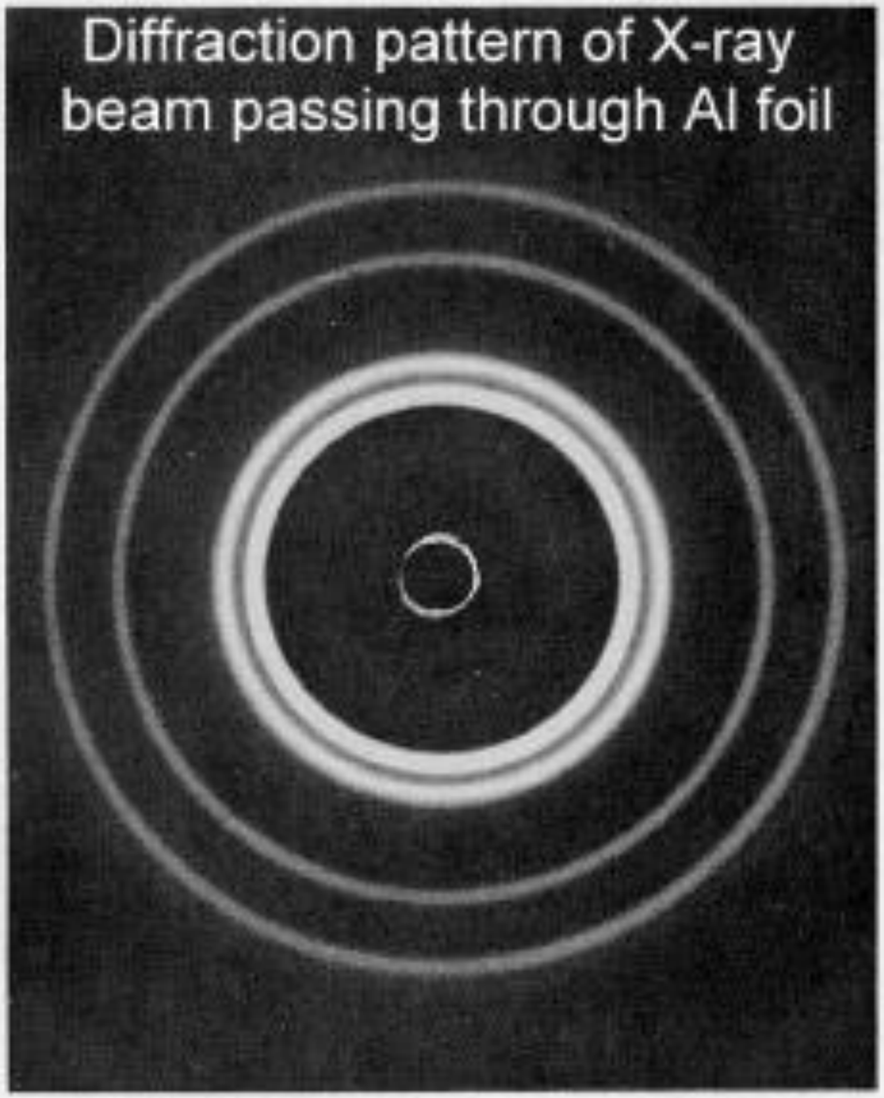
G. P. Thompson's Experiment: Diffraction of 10 – 40 keV electrons by a thin polycrystalline foil

$$\lambda \approx 0.1\ \text{Å} = 10^{-11}\ \text{m}$$

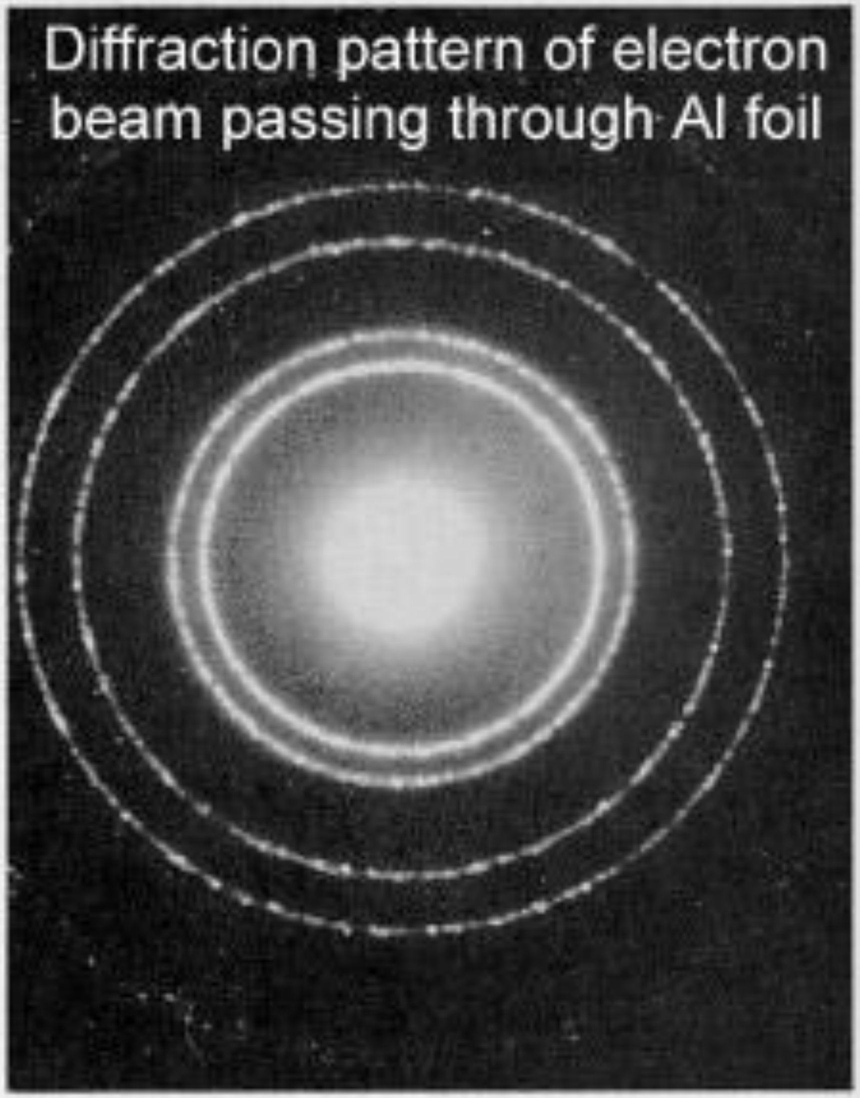




polycrystalline film ⇒ Bragg condition satisfied for any given reflecting plane ⇒ concentric circles

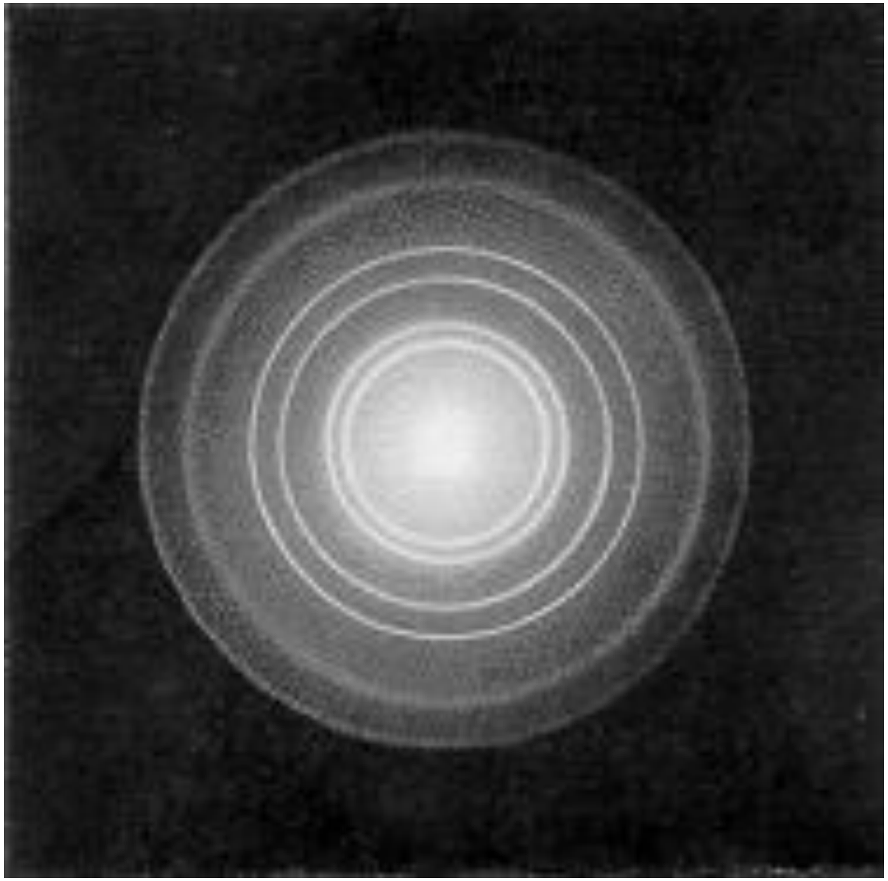


Diffraction pattern of X-ray beam passing through Al foil

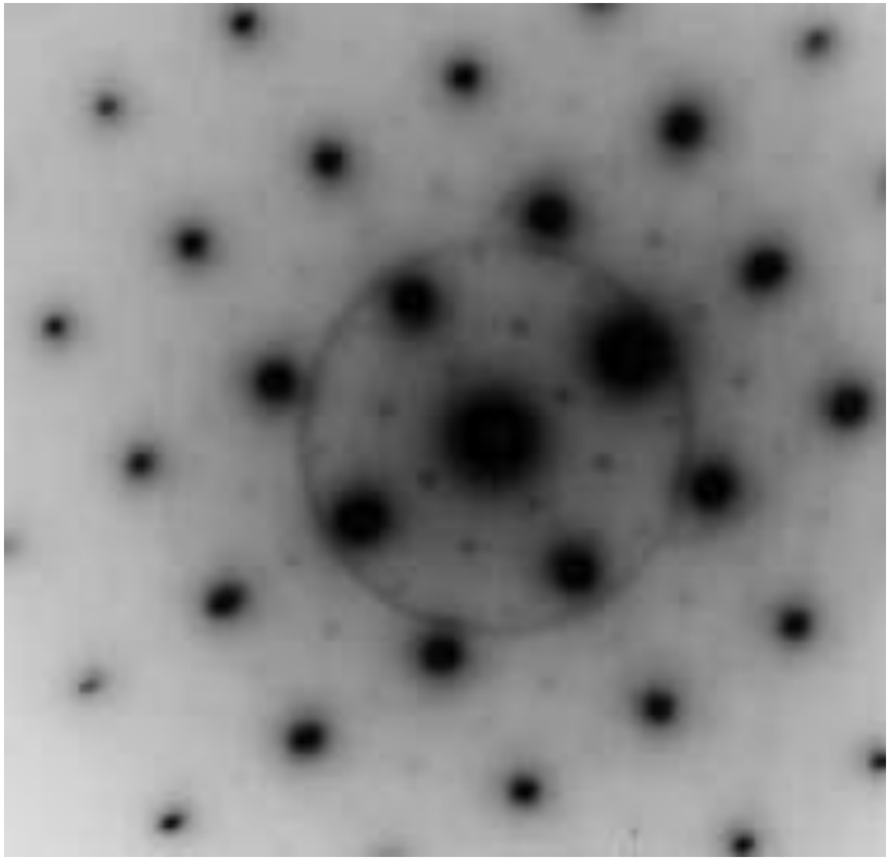


Diffraction pattern of electron beam passing through Al foil

Electron diffraction by polycrystalline aluminum



Laue pattern of electron diffraction by a single crystal

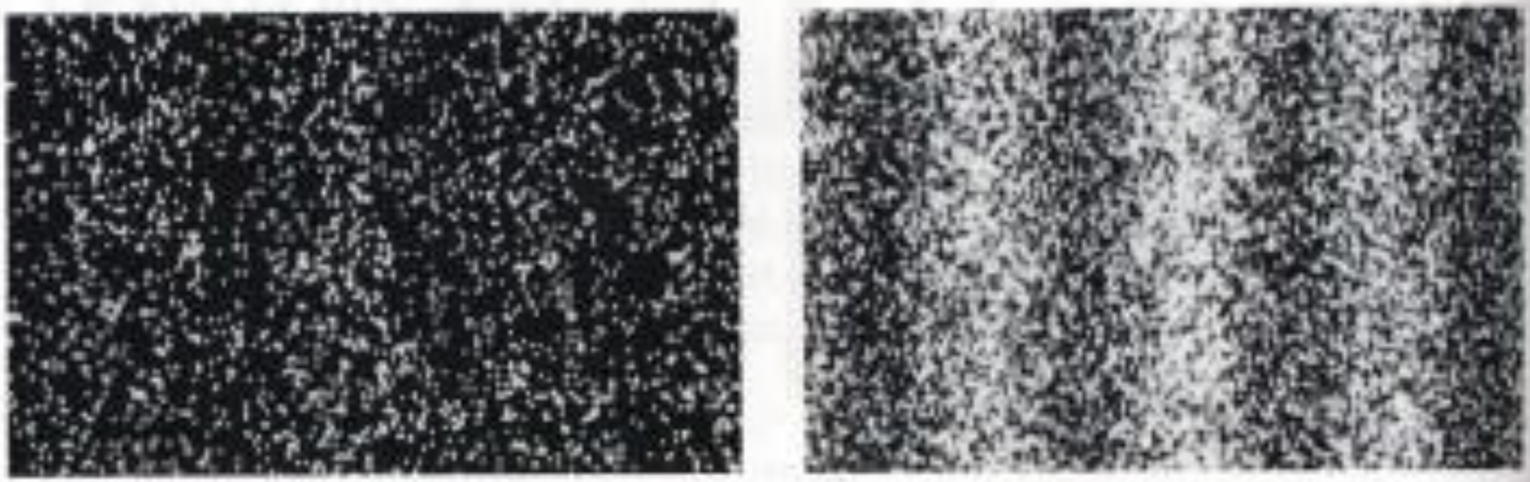


(Courtesy of Prof. Y. Soejima, Dept. of Physics, Kyushu Univ.)

2-slit Interference of Electrons

(a)

(b) After 100 electrons



(c) After 3000 electrons

(d) After 70 000 electrons

Diffraction of Neutrons

λ = several Å down to $<10^{-14}$ m

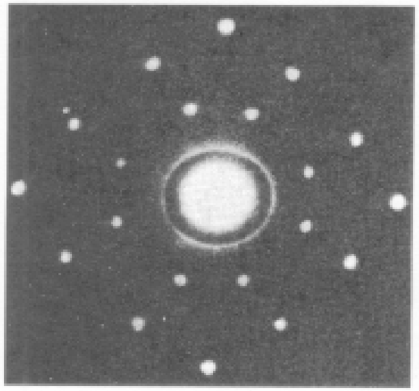
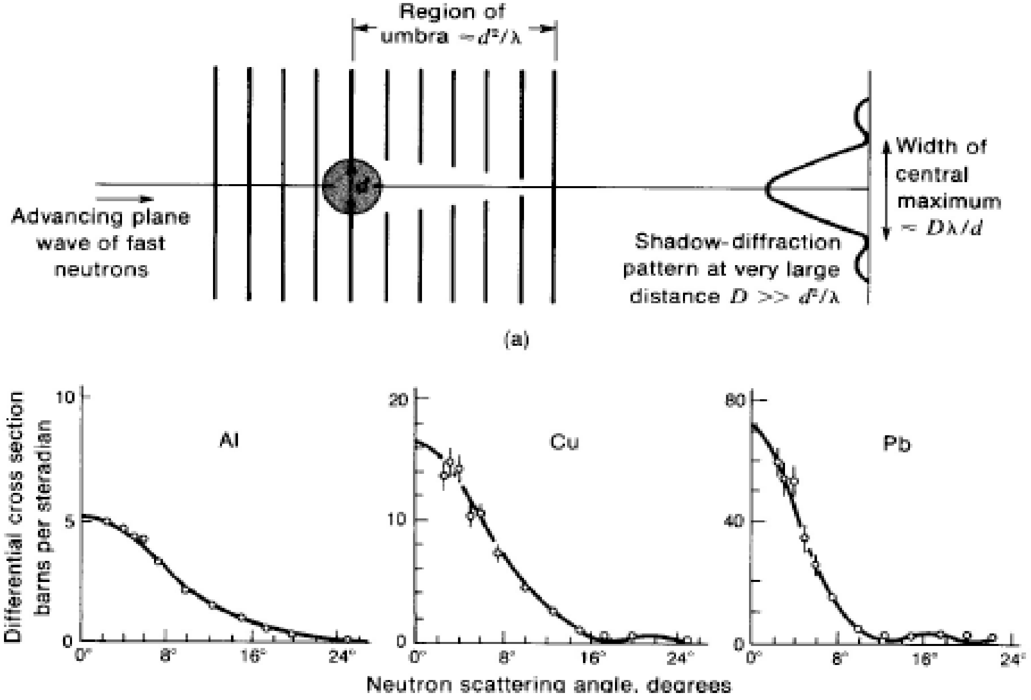
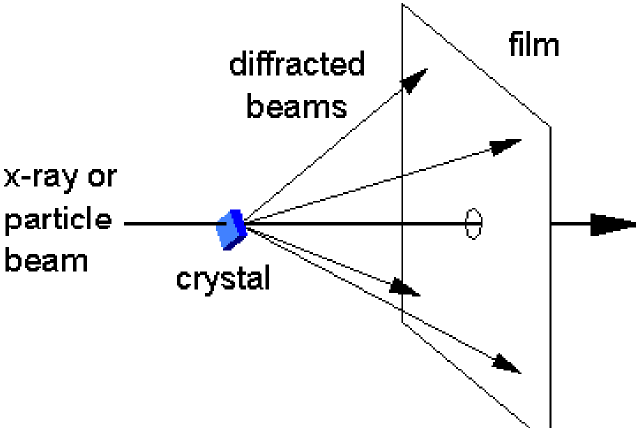


FIGURE 4.7 Diffraction of neutrons by a sodium chloride crystal.

from Krane





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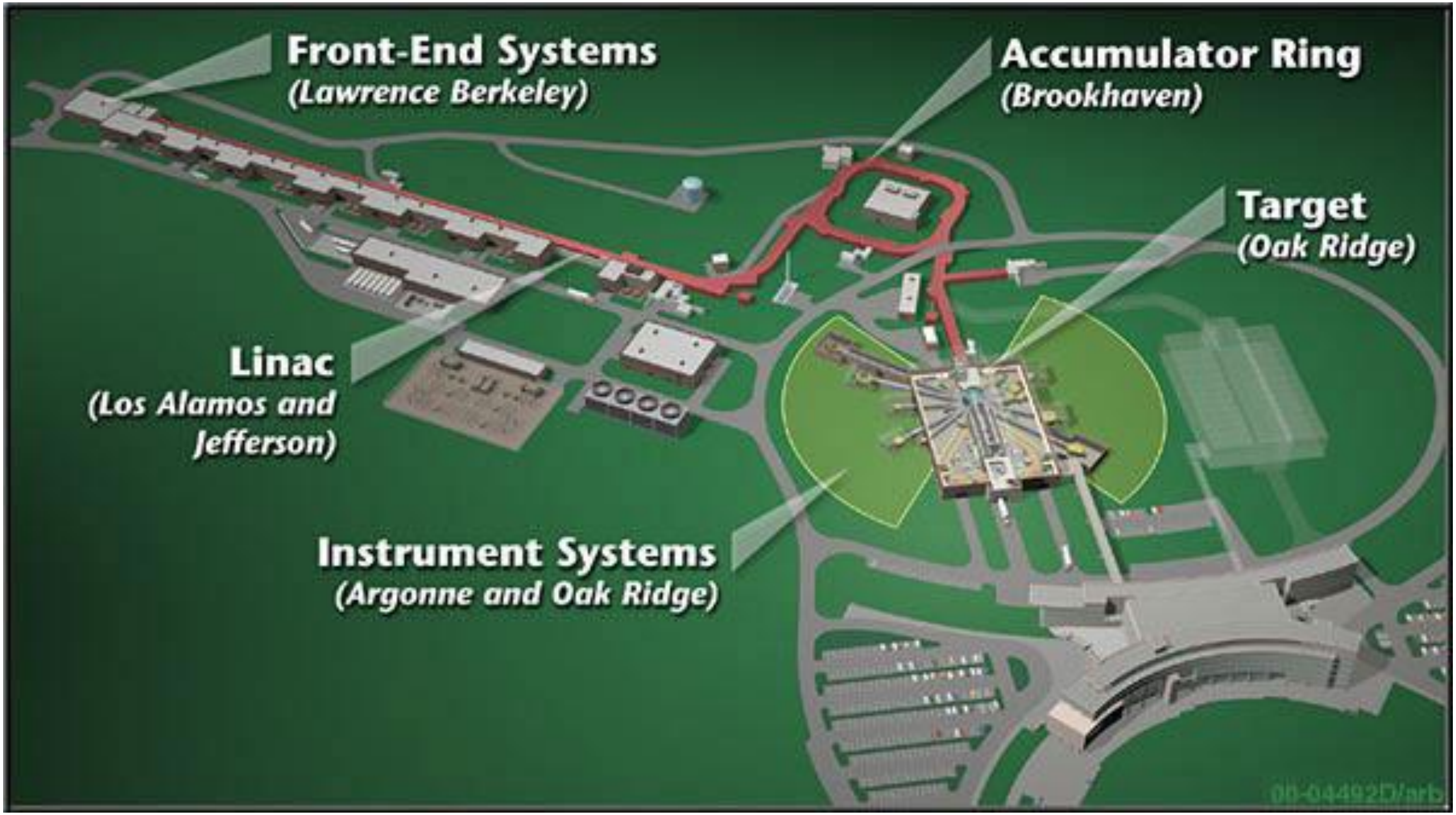
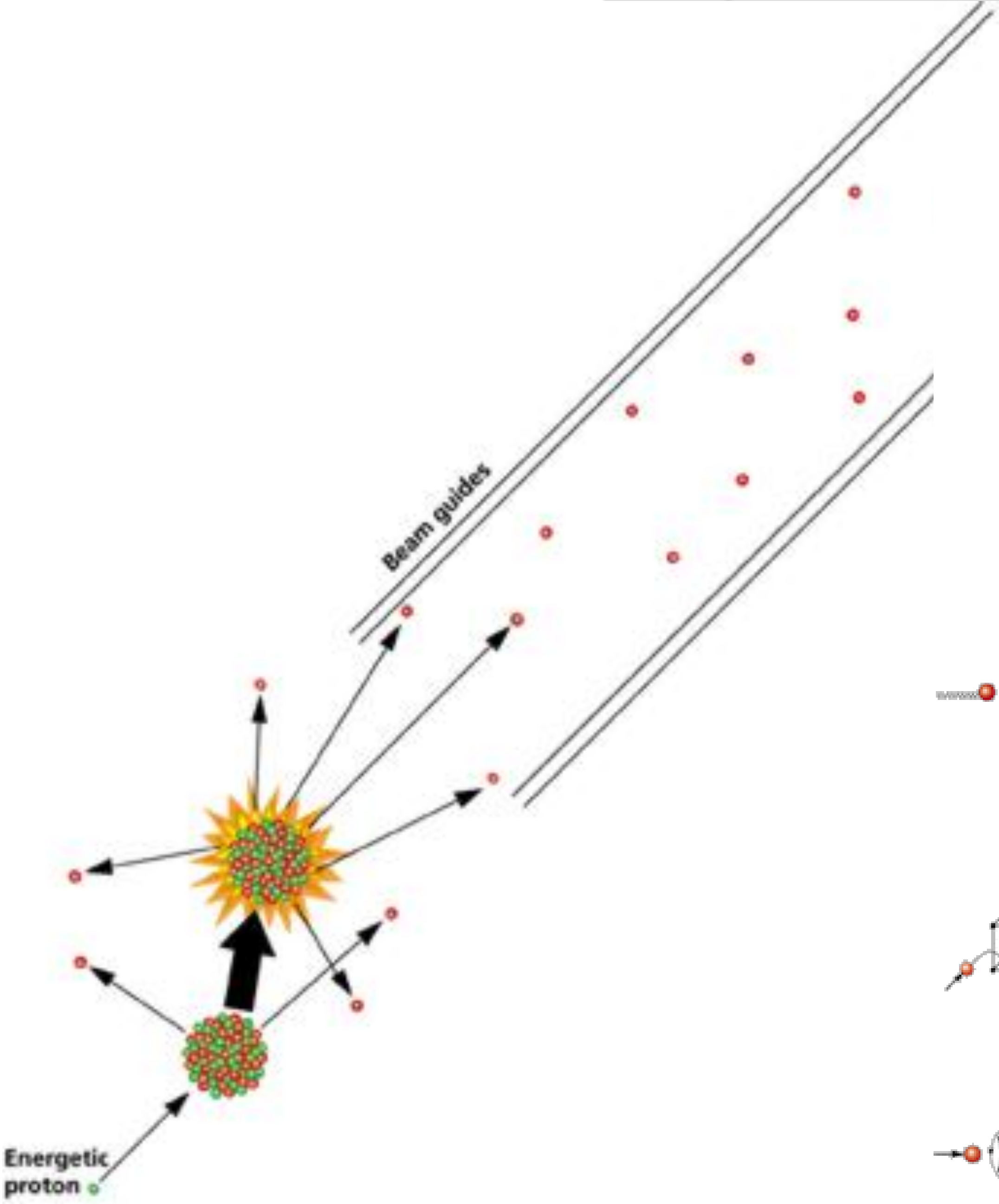
Diffraction of fast neutrons from Al, Cu, and Pb nuclei. [from French, after A Bratenahl, Phys Rev 77, 597 (1950)]

The Spallation Neutron Source (SNS) in Oak Ridge, TN



Why Neutrons?



Neutrons are NEUTRAL particles. They

- are highly penetrating,
- can be used as nondestructive probes, and
- can be used to study samples in severe environments.

Neutrons have a MAGNETIC moment. They can be used to

- study microscopic magnetic structure,
- study magnetic fluctuations, and
- develop magnetic materials.

Neutrons have SPIN. They can be

- formed into polarized neutron beams,
- used to study nuclear (atomic) orientation, and
- used for coherent and incoherent scattering.

The ENERGIES of thermal neutrons are similar to the energies of elementary excitations in solids. Both have similar

- molecular vibrations,
- lattice modes, and
- dynamics of atomic motion.

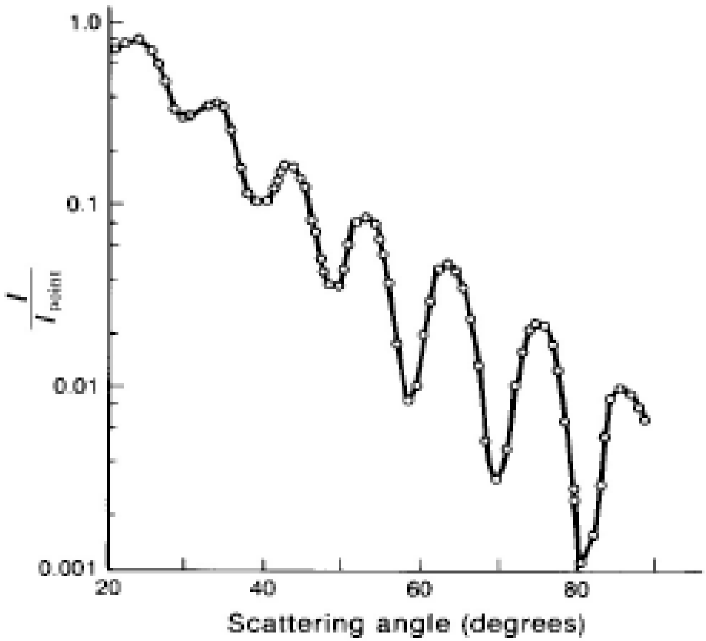
The WAVELENGTHS of neutrons are similar to atomic spacings. They can determine

- structural sensitivity,
- structural information from 10^{-13} to 10^{-4} cm, and
- crystal structures and atomic spacings.

Neutrons "see" NUCLEI. They

- are sensitive to light atoms,
- can exploit isotopic substitution, and
- can use contrast variation to differentiate complex molecular structures.

Scattering of Alpha Particles



Angular distribution of 40 MeV alpha particles scattered from niobium nuclei.
[from French after G. Igo et al., Phys Rev 101, 1508 (1956)]

Crystal Diffraction of Neutral Helium (1930)

$\lambda \approx 1$ Å

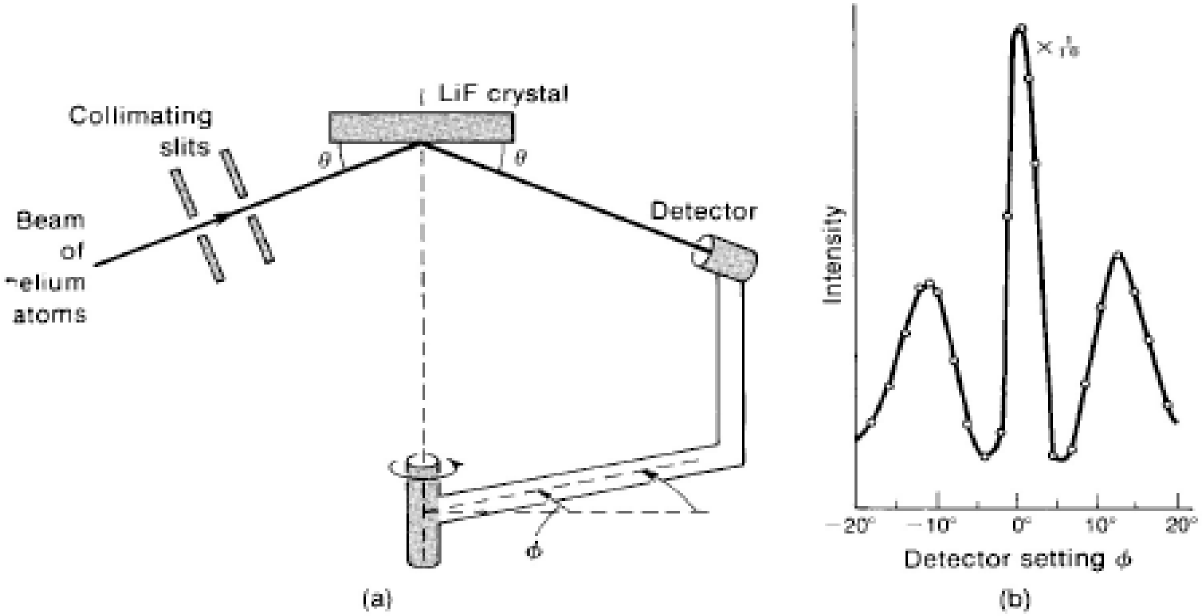
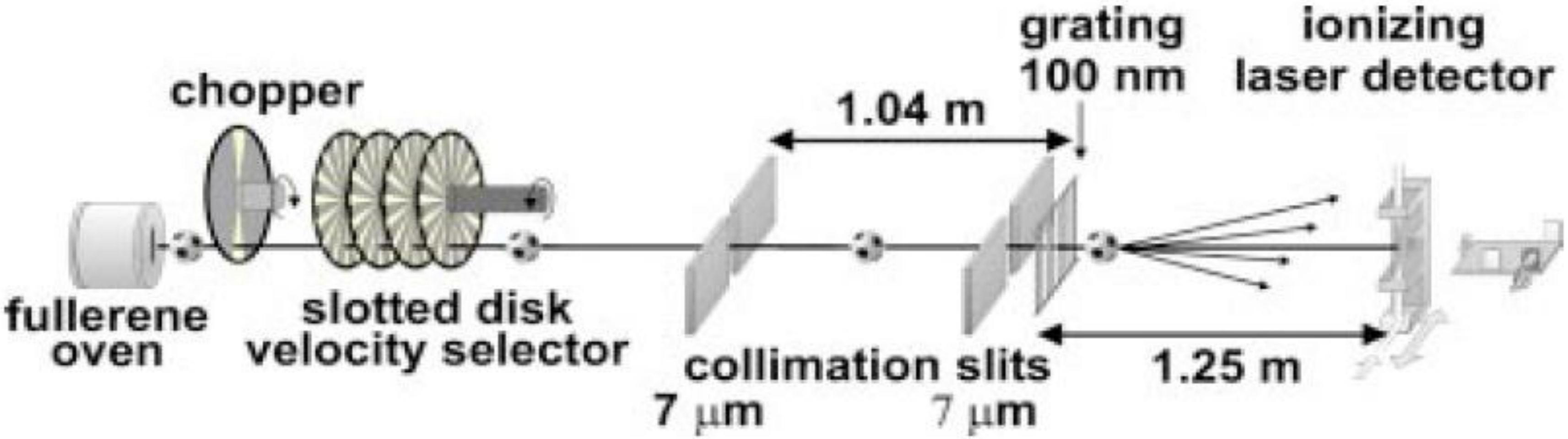


Fig. 2-16 (a) Experimental arrangement used by Stern et al. *to investigate crystal diffraction of neutral helium atoms. (b) Experimental results showing central reflection peak* ($\phi = 0°$)*, plus first-order diffraction peaks* ($\phi = 11°$)*. In the experiment,* $\theta = 18.5°$.

from French after Estermann and Stern, Z Phys 61, 95 (1930)

Interference of Molecules



Fullerene molecule C60 , consisting of 60 carbon atoms