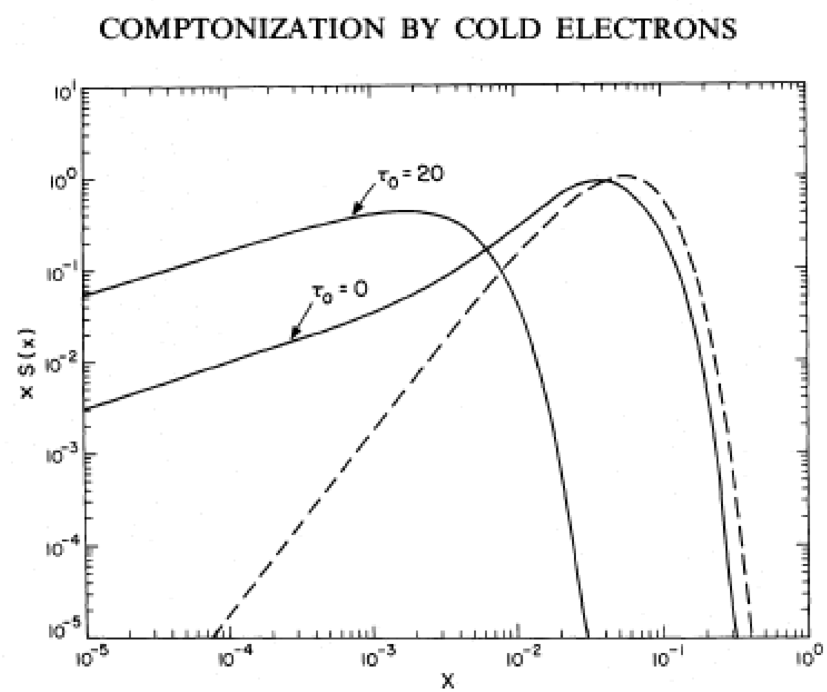
Comptonization

- The output spectrum depends on the distribution function of both the electrons and photons
- If the electrons are 'cooler' than the photons the spectrum is 'down scattered' if the electrons are hotter it is up scattered.
- If $E_{photon} < 4kT_e$ photons gain energy gas cools
- If $E_{photon} > 4kT_e$ electrons gain energy gas heats
- Up scattering tends to produce a power law distribution

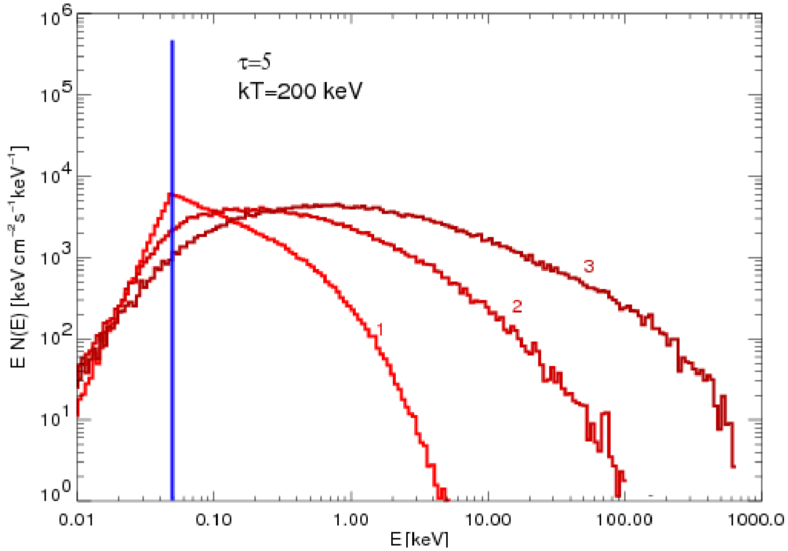


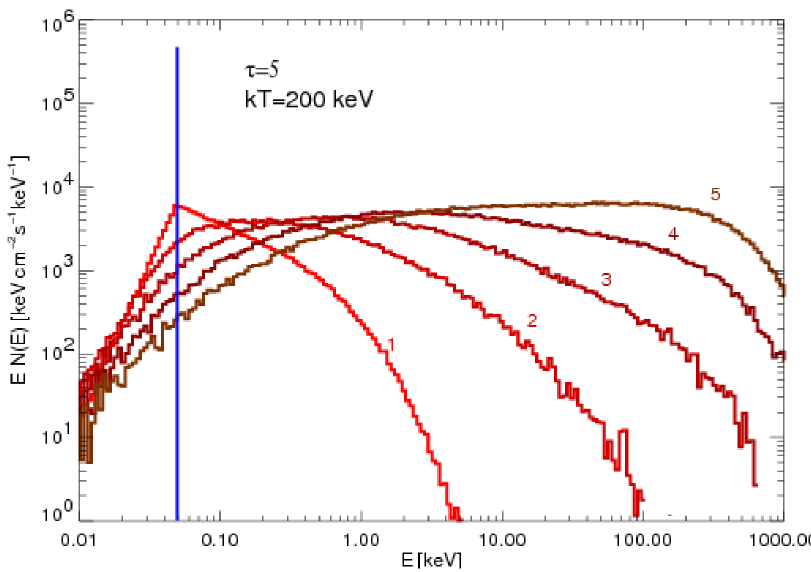
Compton scattering

- Each scattering tends to produce a broad distribution of photons and **the sum** tends to a power law shape
- X-ray spectra of galactic and extragalactic black holes can be well explained by comtptonized spectra with kT_e~150 kev, y~1 ($y=4kT_e/m_ec^2(\max(\tau,\tau^2))$)

When averaging over angles the free parameters of Compton scattering are the probability of interacting (parameterized by τ - the optical depth) and the electron temperature (T_e) as long as the effective temperature of the photons is $<<T_e$

- http://pulsar.sternwarte.uni-erlangen.de/wilms/teach/radproc/radproc0201.html





Relative Power in Compton and Synchrotron Radiation

$P_{IC}=4/3\sigma_T c^2 U_{rad}\beta^2\gamma^2$

net inverse-Compton power gained by the radiation field and lost by the electron.

Synchrotron power

$P_{synch}=4/3\sigma_T c^2 U_B\beta^2\gamma^2$

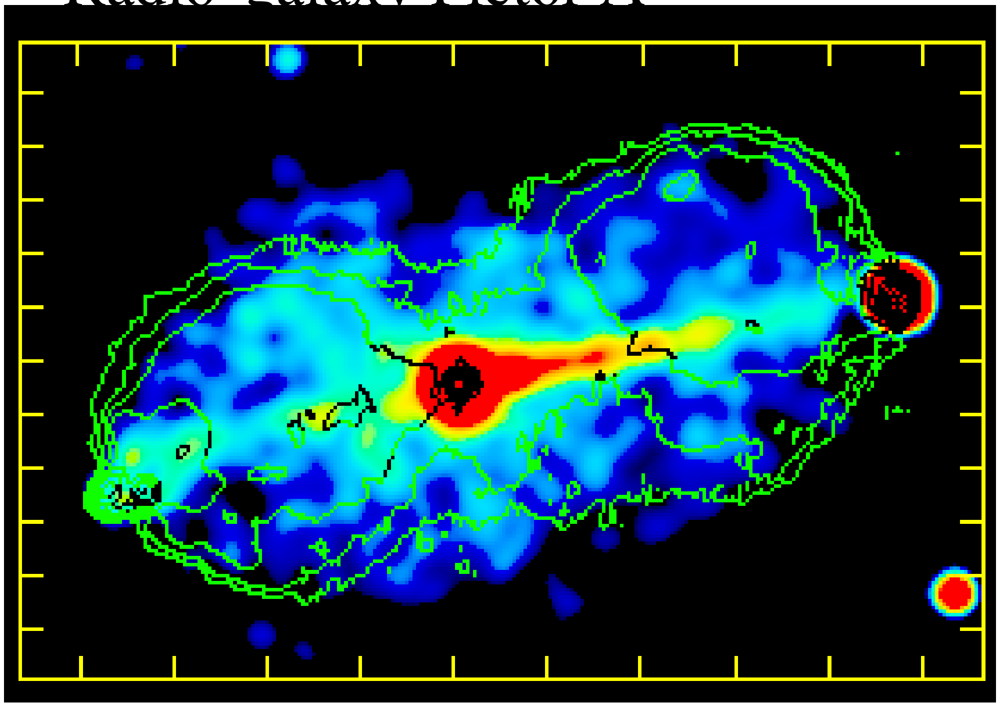
Where $U_B=B^2/8\pi$ is the energy density of the magnetic field

And U_{rad} is the energy density of the photon field

$\beta=v/c$; $\gamma=(1-\beta^2)^{-1/2}$

Ratio of Synchrotron to Compton is **U_B/U_{rad}**

'Radio' galaxy Pictor A



Radio image (synchrotron) green contours

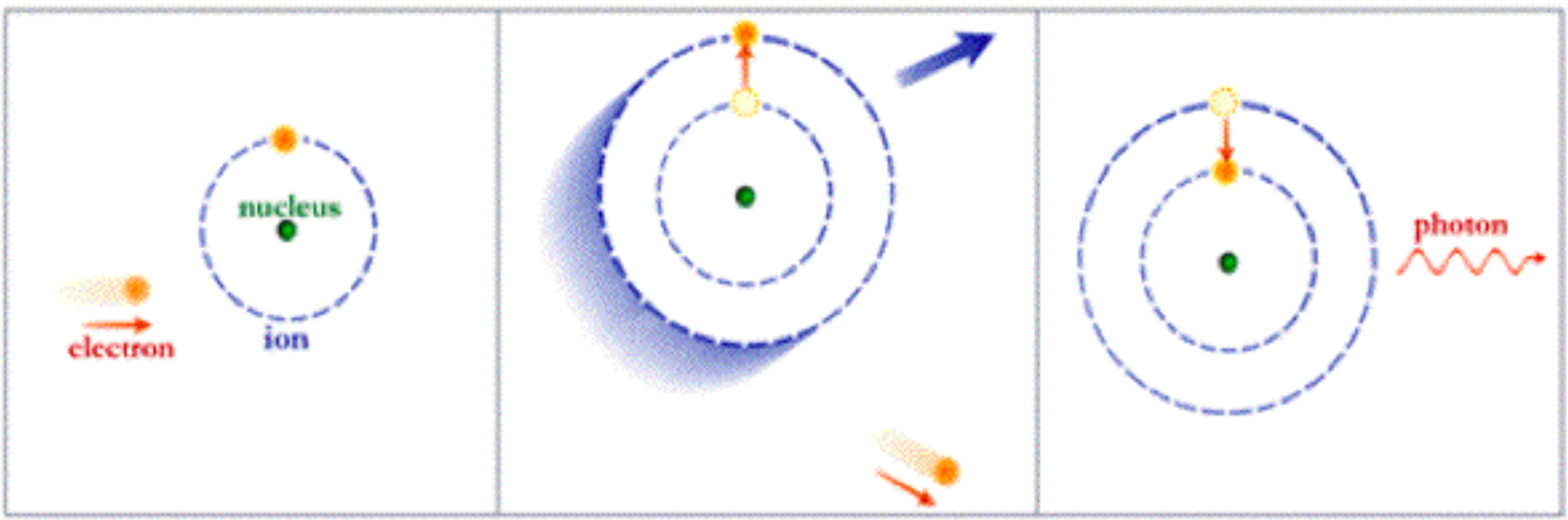
IC image (x-rays, color) Hardcastle and Birkinshaw 2004

LINE EMISSION

- Excitation of atoms by:
  - Thermal collisions
  - Radiative excitation
- Then radiative de-excitation

the most common mechanism of line emission is from collisionally excited radiative decay

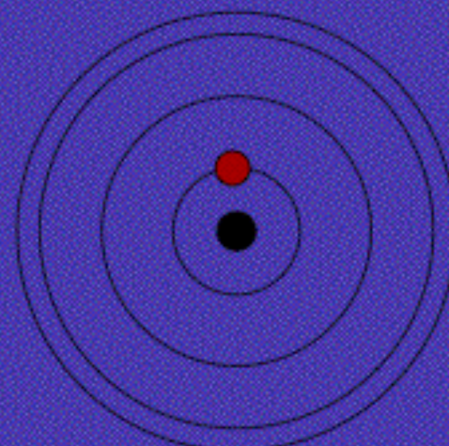
Radiative transition rate (aka "Einstein A value") is the expected number of spontaneous transitions per second/atom from one level to another $A_{ij}=1/t_{radiative}$



Specific Emission

Electron in bound orbitals around an atomic nucleus of nuclear charge Z can produce radiation at specific frequencies or energies, since electrons can only orbit the atomic nucleus in a well-defined set of allowed orbits.

Each orbit is associated with an electron energy, so are sometimes called energy levels. An electron has to gain energy to move from an inner to an outer energy level. An electron loses energy when moving from an outer to an inner energy level.



Each element has its own unique set of energy levels:

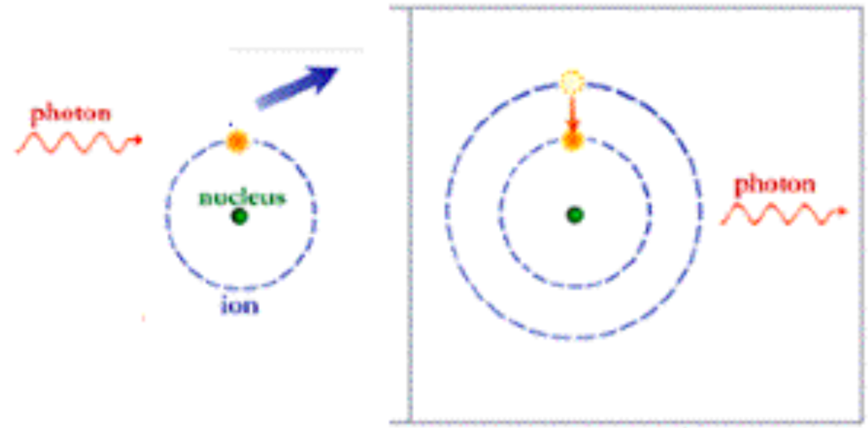
$$E_N = -\frac{13.58 Z^2}{N^2} \text{electron volts (eV)}$$

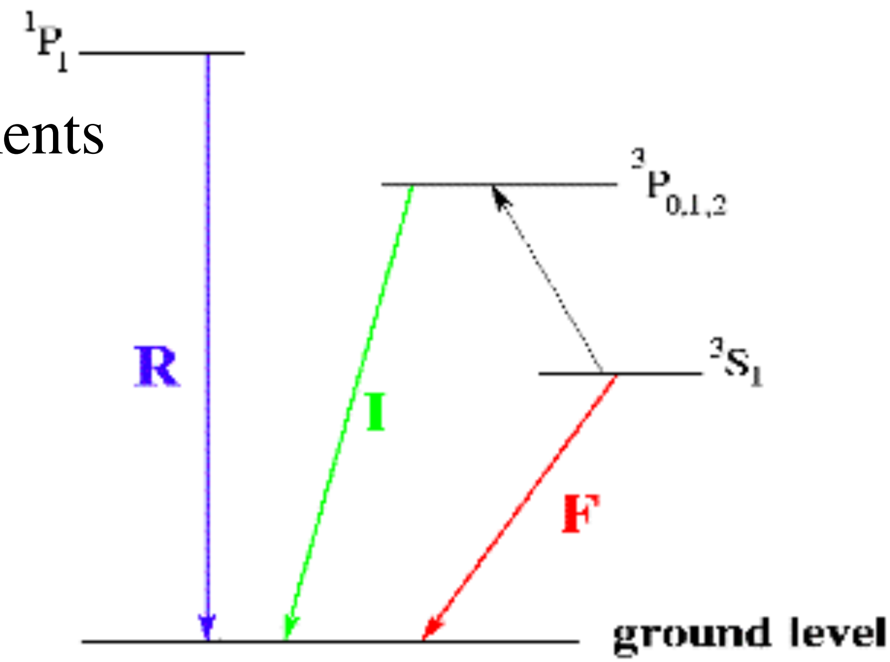
TYPES OF LINE EMISSION

- Fluorescence:
  - Needs L-shell electrons
  - Photoionization, then either:
  - 2p->1s radiative transition
  - *or* Auger ionization
  - **Fluorescence yield** measures ratio

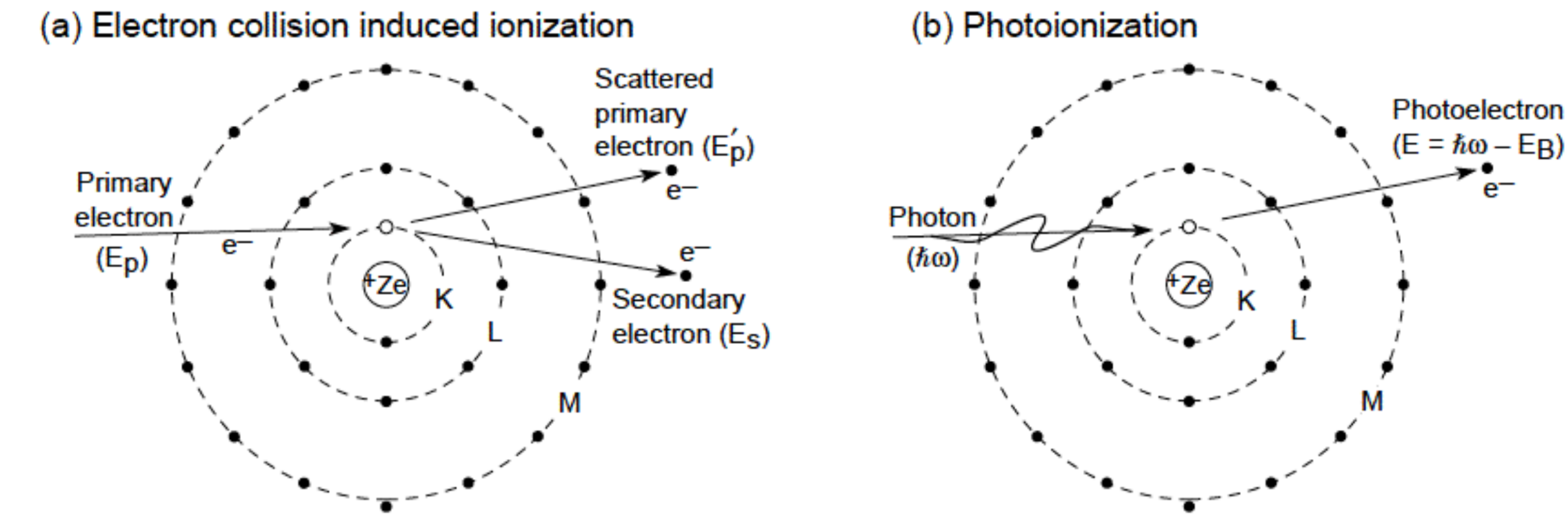
Yield~Z^4 important for high Z elements

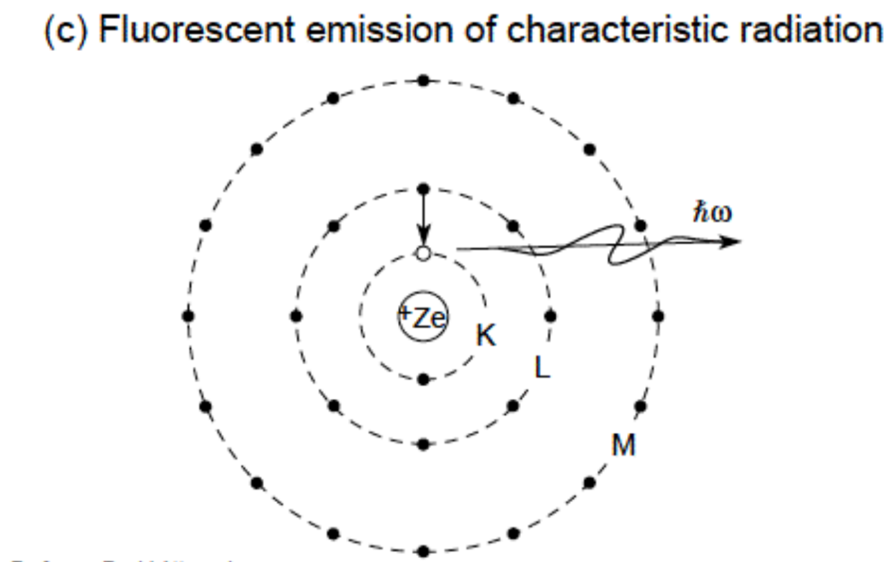
- Recombination (ionized)
  - He and H-like are most important
  - Triplet: forbidden, resonance, intercombination





From R. Smith



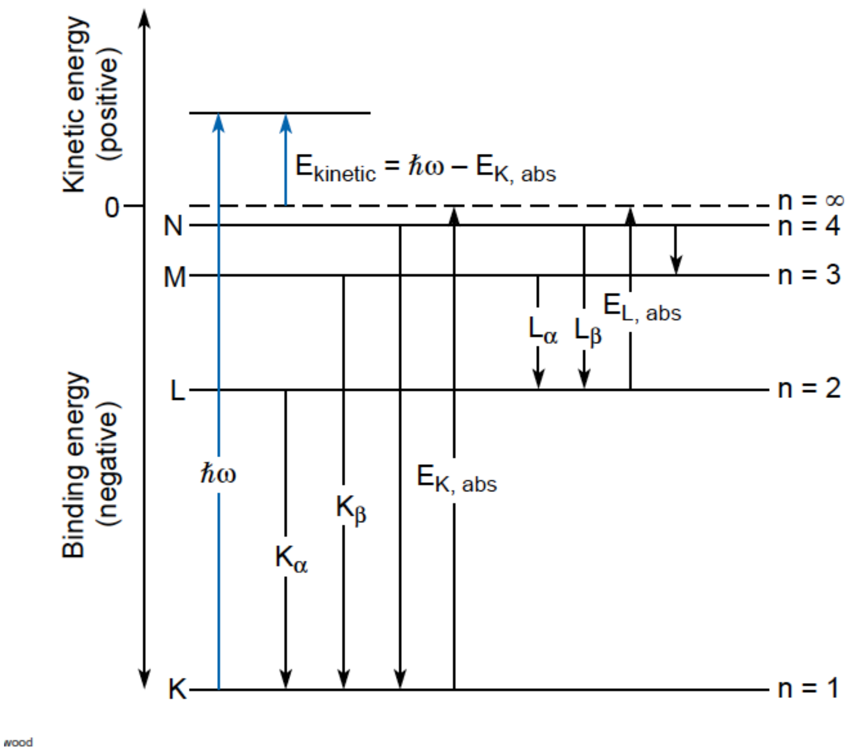


3 ways to produce a Photon via 'atomic' process (an incomplete set)

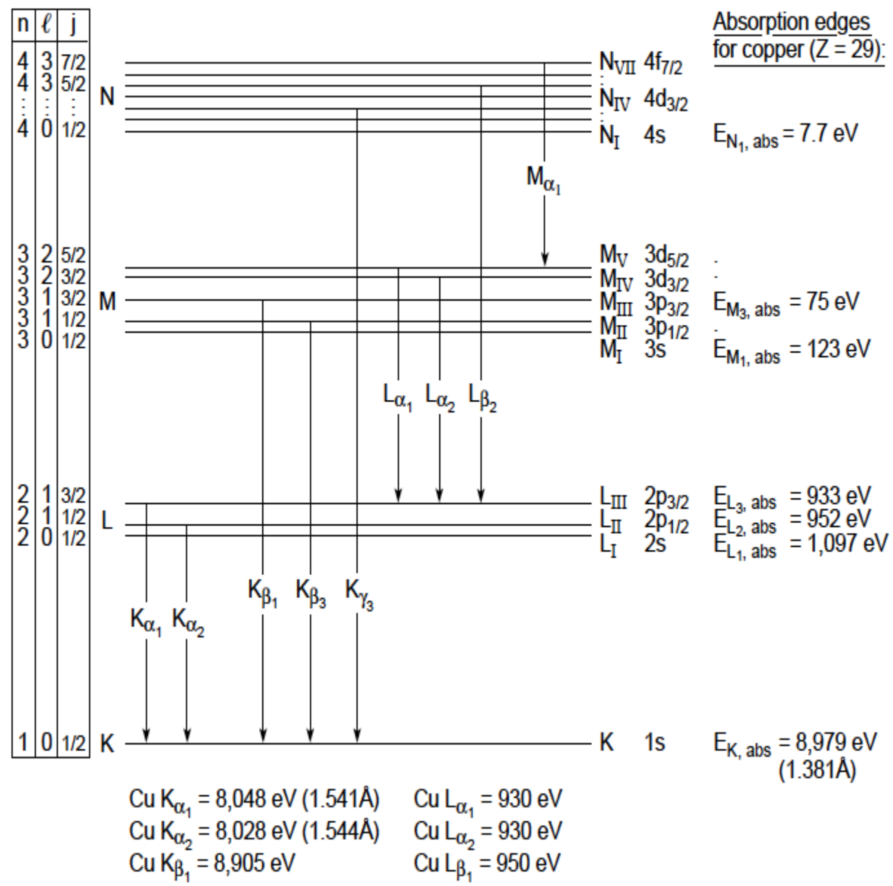
Professor David Attwood

- # Generic Atom

Energy Levels, Absorption Edges, and Characteristic Line Emissions for a Multi-Electron Atom



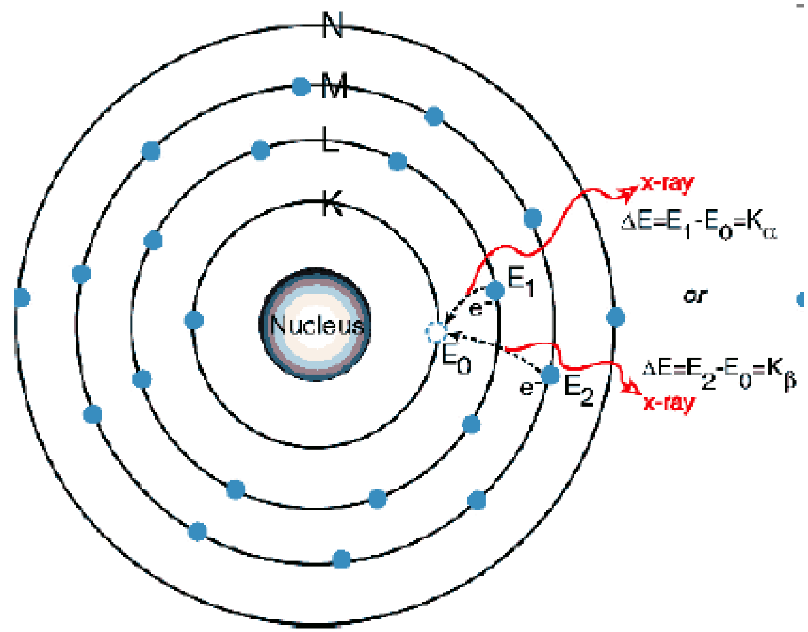
Energy Levels, Quantum Numbers, and Allowed Transitions for the Copper Atom



- # Copper Atom

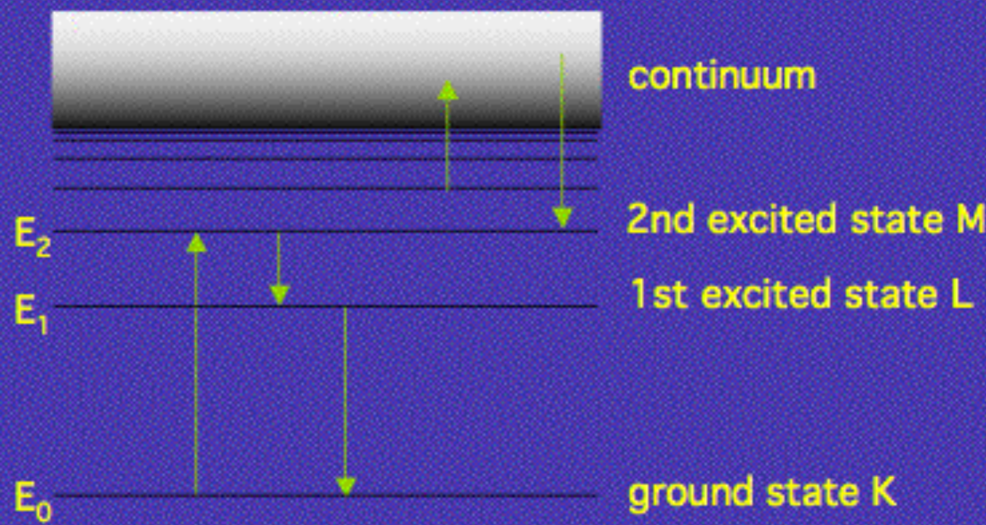
Flourescence

- X-ray fluorescence



  – discrete lines!

Electronic Processes



$E_0 < E_1 < E_2$ (it takes energy to move the electron away from the positively charged nucleus)

Atomic Energy Level Diagram (Schematic)

Excitation: an electron absorbs radiation of energy $E = E_N - E_M$ and jumps from energy level M to level N (M<N)

De-excitation: an electron jumps from level N to level M (M<N) and emits a quantum of radiation (a photon) of energy $E = E_N - E_M$

Ionization: an electron jumps from level N to the continuum (E_∞) after absorbing a photon of energy $E > E_N$. The energy required to ionize an atom from its ground state is called the **Ionization Potential**.

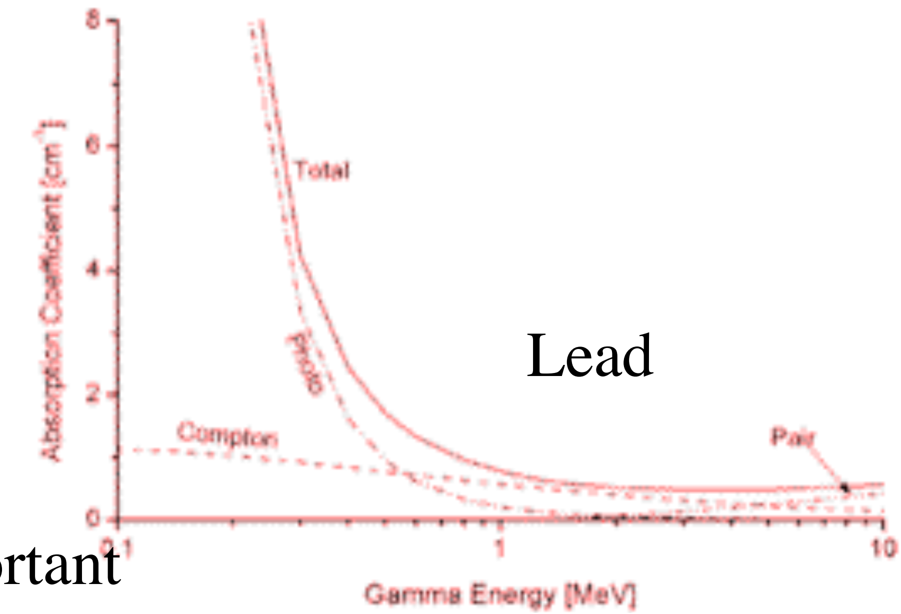
Recombination: A free electron is captured by an atom into some energy level N.

Absorption of X and γ-ray Photons

- Absorption processes
  - Photoelectric absorption
  - Ionized gas: warm absorbers
  - Absorption lines

absorption of γ-rays via pair creation, photoelectric effect, Compton scattering (photons reduced in energy, not absorbed).

X-ray and γ-rays are very penetrating radiation -but A 1 keV x-ray is totally absorbed by ~0.01gm of material (~10^{22} atms/cm^2)



In γ-rays pair creation is also important

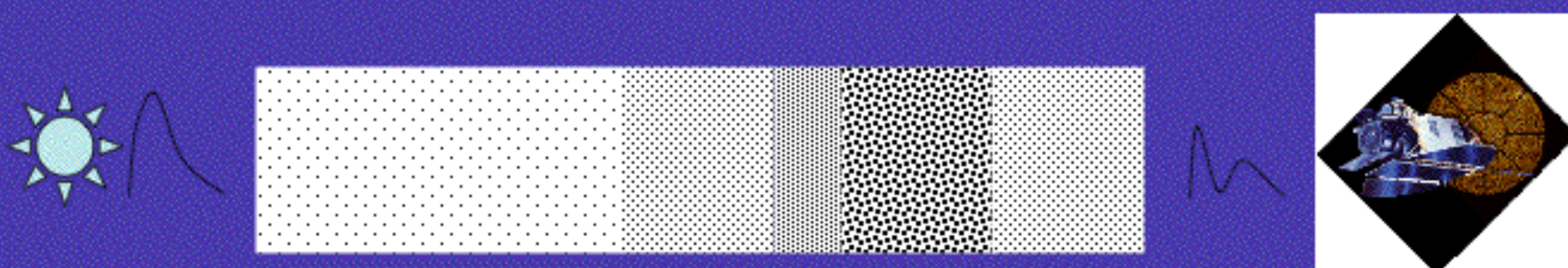
Absorption

As radiation passes through a medium, in general the medium will absorb some of the radiation, and emit some radiation. Thus the radiation received at a detector will be different from that emitted by the source. For a source of intensity I_0 whose light passes through an absorbing medium, the observed intensity I is

$$I = I_0 \exp^{-\tau}$$

where τ is the optical depth of the medium. τ is sometimes expressed in terms of an absorption cross-section σ and a column density N (the number of particles in a cylindrical column of unit area in the medium)

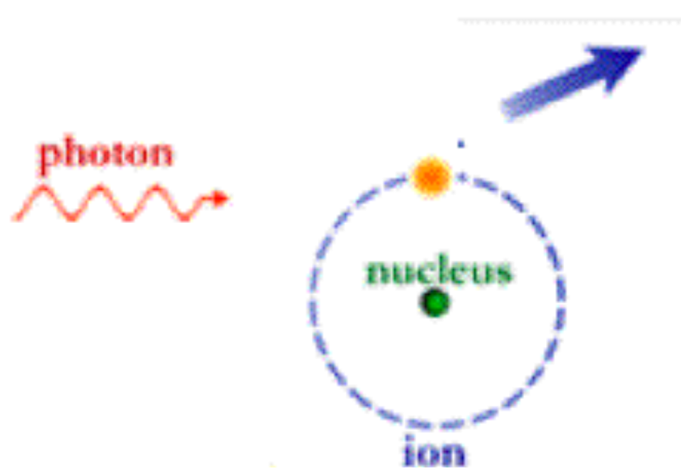
$$\tau = N\sigma$$



PHOTOELECTRIC ABSORPTION

- Bound-free ionization of e^- by photon
- Threshold energy $E_{th}=h\nu$ depending on ionziation potential of atom (i.e. on Z)
- Abundant elements (C,N,O) are light: absorption dominant at soft (<1 keV) X-rays

Continuum ⇒



⇐ Observer

PHOTOELECTRIC ABSORPTION

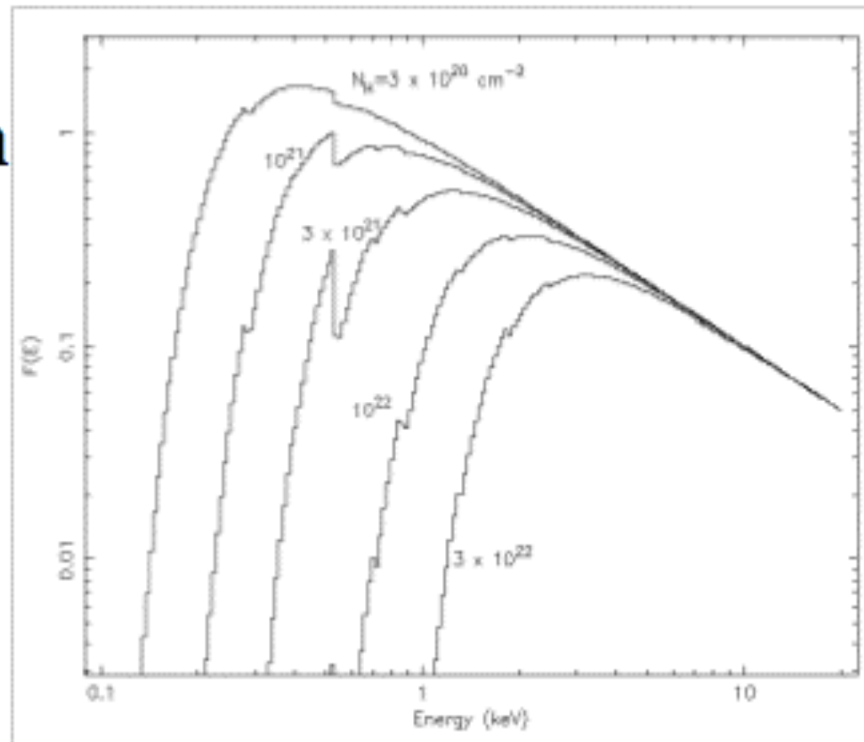
$N_H =$ Equivalent hydrogen column density (cm^{-2})

$\sigma(E) =$ cross section (cm^2)

$\tau = \sigma(E) N_H =$ optical depth

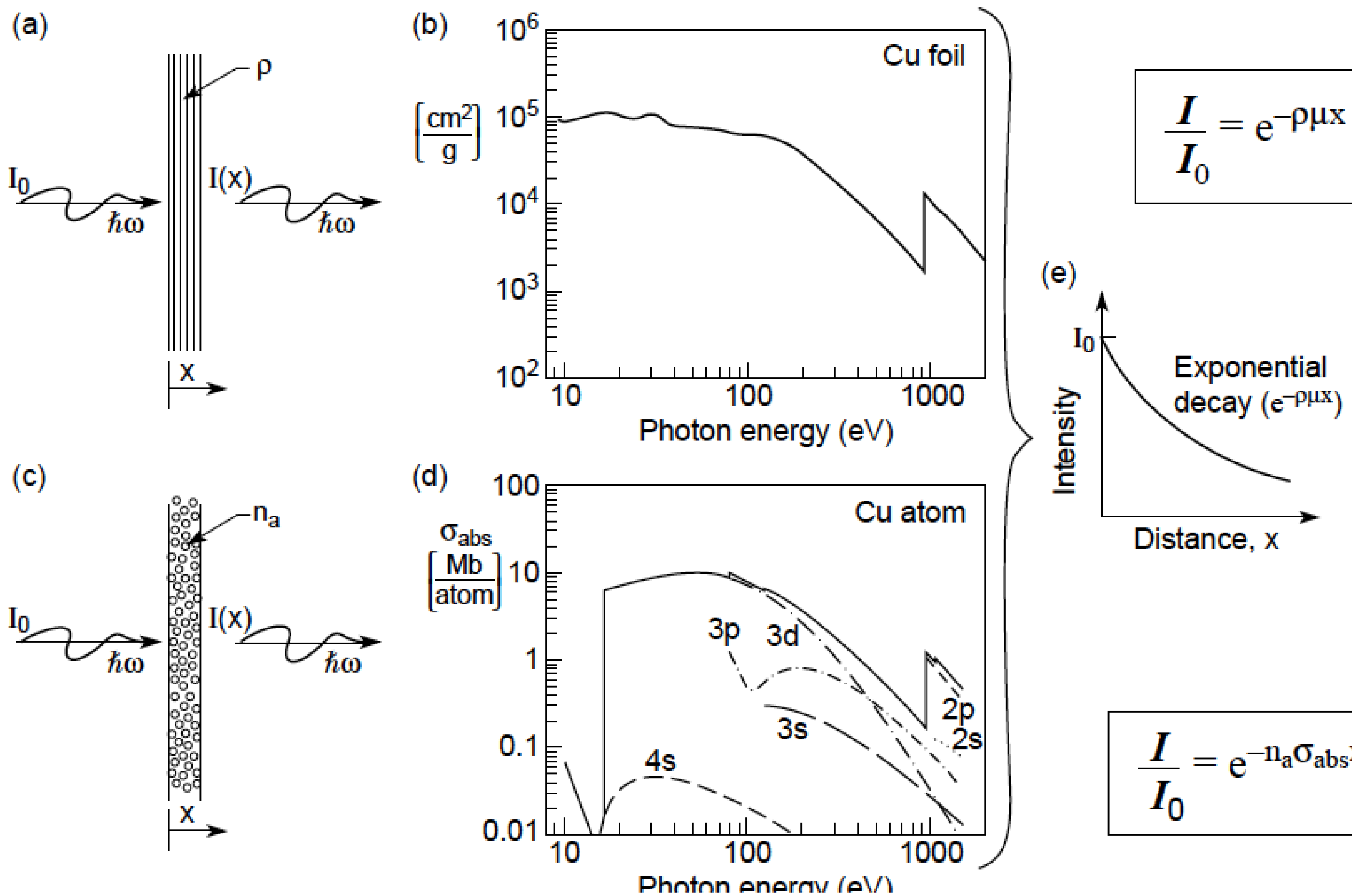
$$F(E) = AE^{-\Gamma} e^{-\sigma(E) N_H}$$

$$\sigma(E) \approx E^{-3}$$



Profile dominated by bound-free edges of abundant elements

Photoabsorption by Thin Foils and Isolated Atoms



$$\frac{I}{I_0} = e^{-\rho\mu x}$$

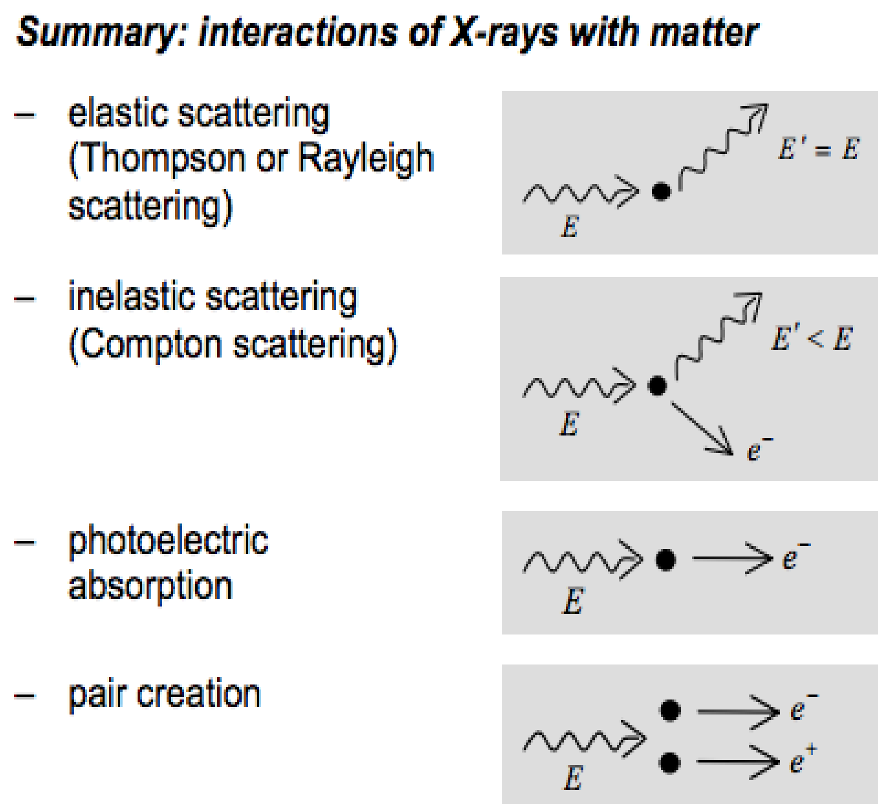
$$\frac{I}{I_0} = e^{-n_a \sigma_{abs} x}$$

X-ray Absorption

$I = I(0,E)\exp(-\sigma n)$; σ is the cross section per atom as a function of energy; n is the number of atoms

For normal materials

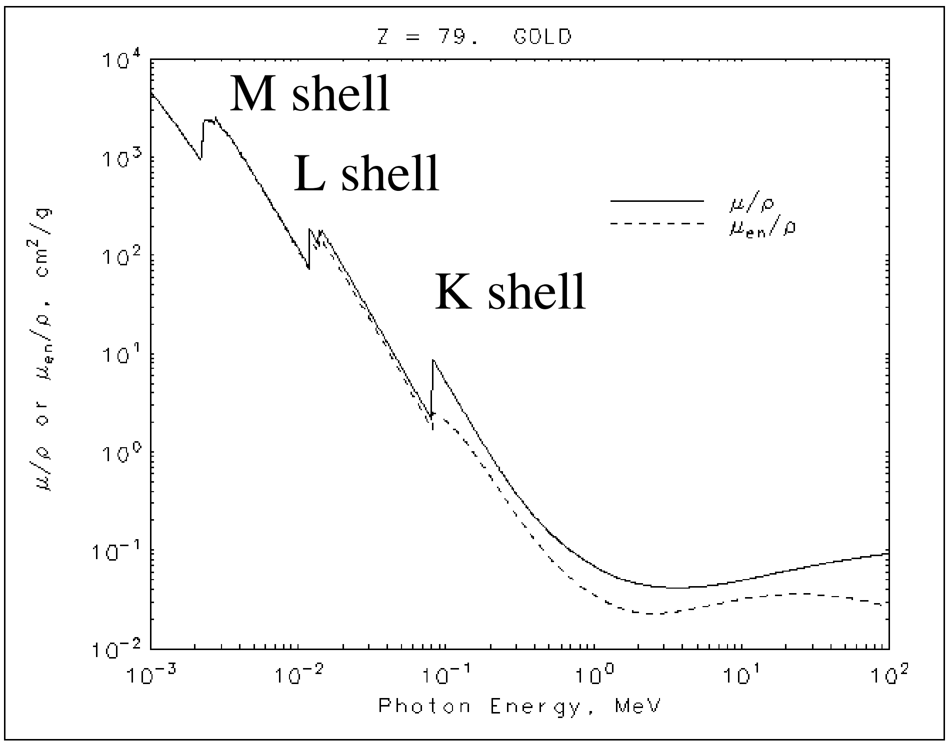
- E<100 kev photoelectric absorption dominates
- 100 keV<E<1 MeV Thompson and Compton scattering dominate
- E> 1 MeV ($2m_ec^2$) pair production dominates
- when photoelectric absorption dominates there are prominent "absorption edges" characteristic of the binding energies of electrons in specific atoms (or ions)



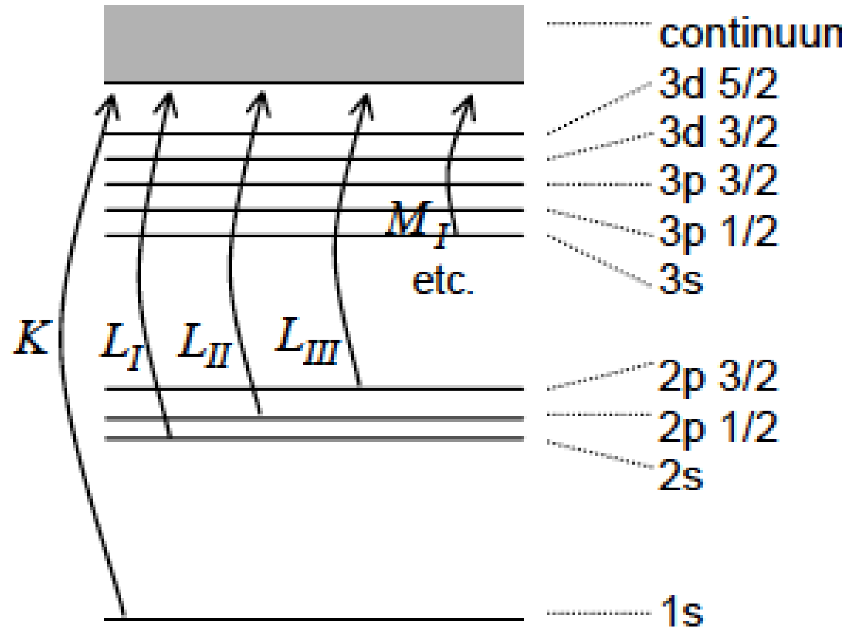
from http://www2.fkf.mpg.de/keimer/lecture/Scattering_I/MS_6.pdf

energy of absorption edge is characteristic of specific element.
E.g. for *K*-edge: $E_K \sim (Z(Z-1))13.6\text{eV}$
where Z = nuclear charge

Gold- Absorption Cross Section vs Energy



log Energy (MeV)

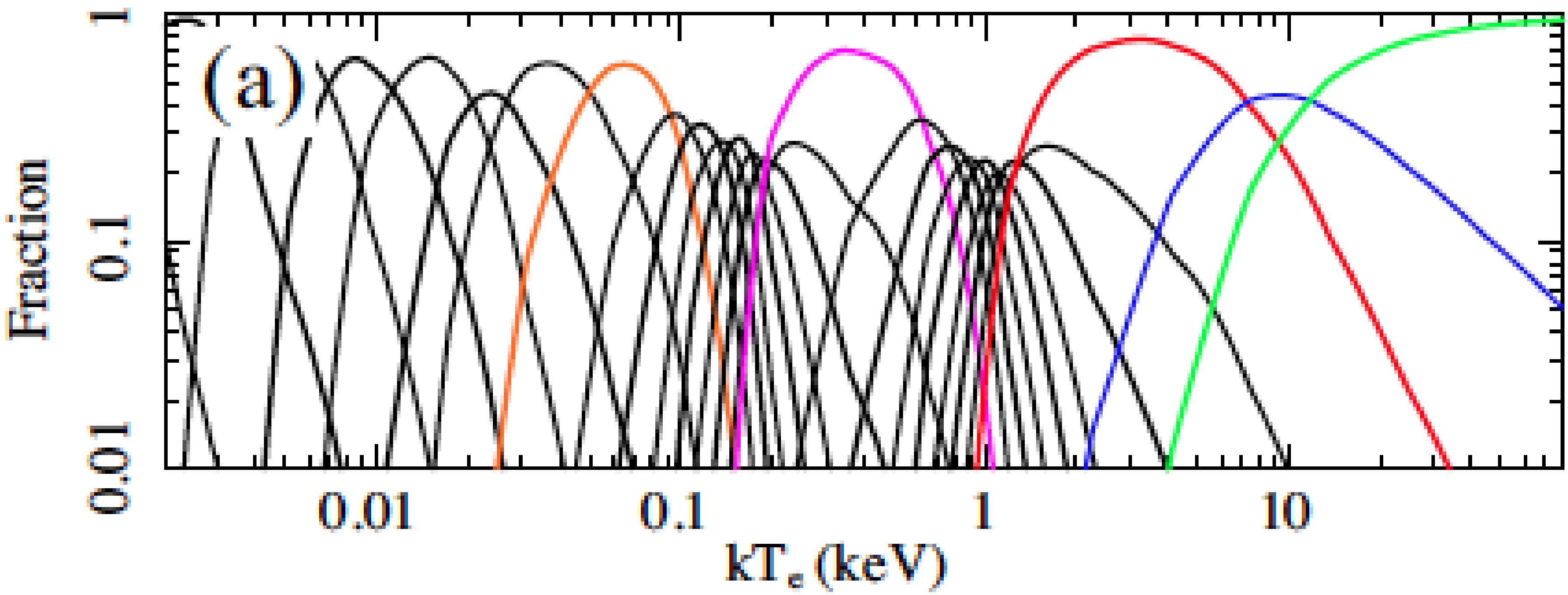


.

– strong ***energy dependence*** of absorption coefficient.
This is the origin of the diminishing relative importance of photoelectric absorption with increasing energy.
– ***absolute magnitude*** of *cross section* depends strongly on *Z*.

Collionsially Ionized Plasma

- The fraction of Fe that is in a given ionization state as a function of the temperature (red is He-like Fe, blue is H-like Fe, magenta is is Ne-like (Fe+16), orange is Ar like,Fe+8)
- **As gas gets hotter it gets more ionized**



IONIZED ABSORBERS

- In practice gas may be hot (collisionally ionized) or, more importantly, photoionized
- Ionization parameter (flux/density):

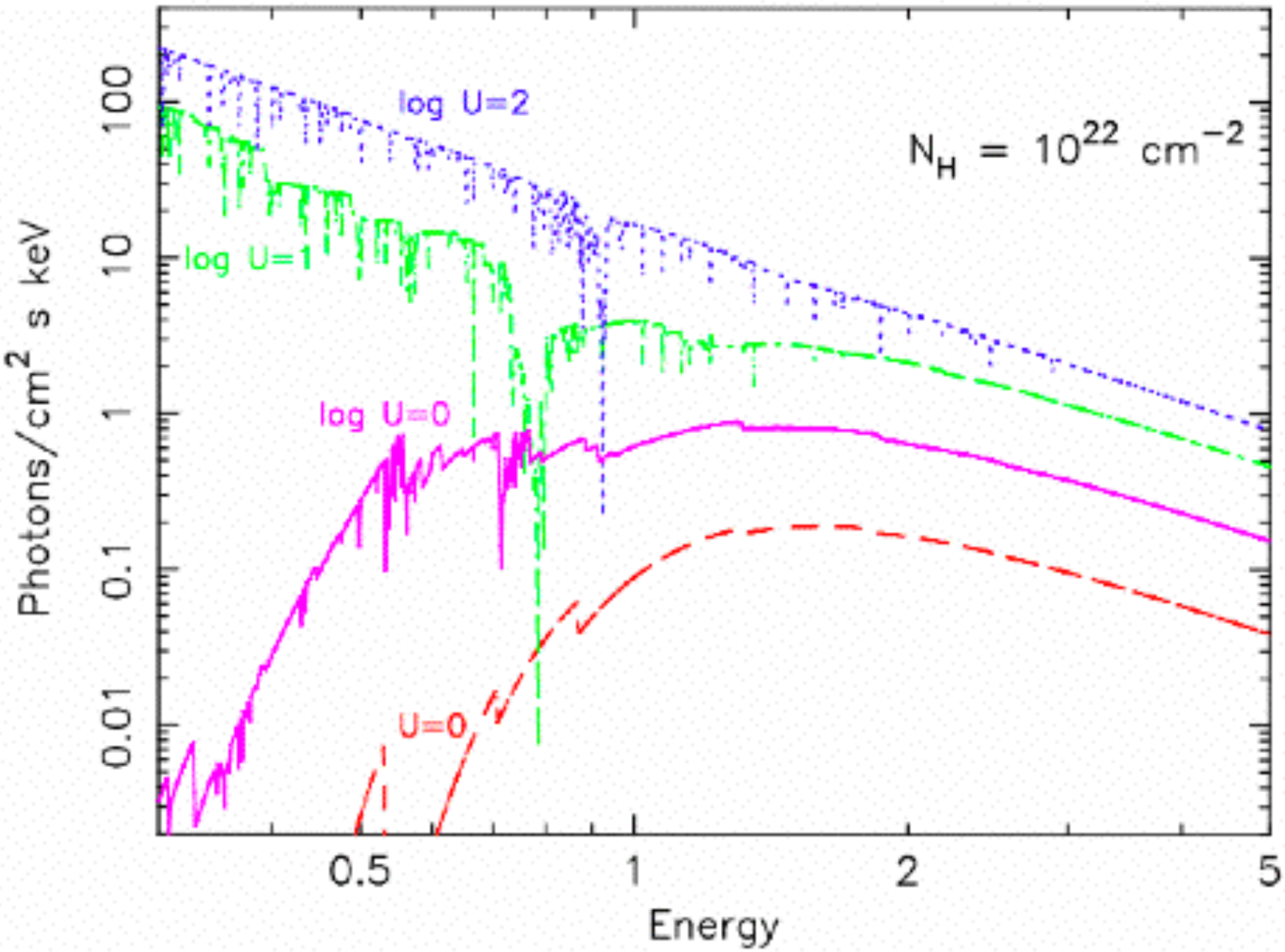
$$\xi \equiv \frac{L_X}{n_e R^2} \quad \text{Tarter, Tucker \& Salpeter (1969)}$$

$$U_X \equiv \frac{N_X}{4\pi R^2 n_e c} \qquad \text{Davidson (1974)}$$

$$L_X \equiv \int_{E_{\min}}^{\infty} L(E)\,dE \qquad N_X \equiv \int_{E_{\min}}^{\infty} \frac{L(E)}{E}\,dE$$

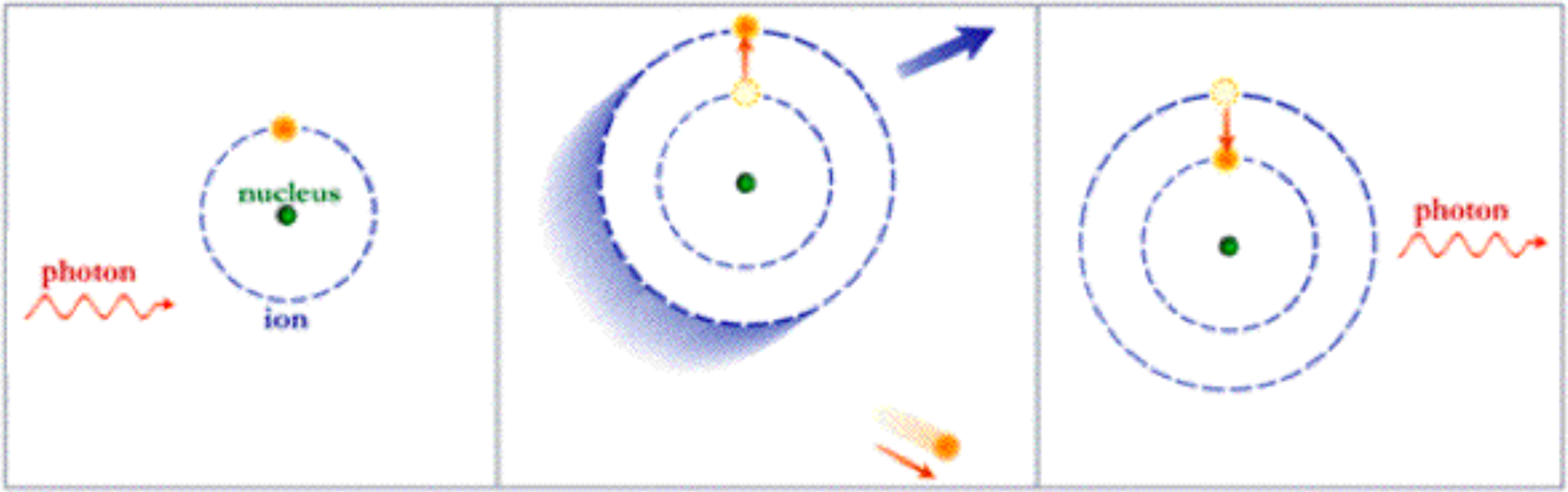
$E_{\min} = 13.6\text{eV}$, 0.1 keV, 0.7 keV (Davidson, Netzer, George)

IONIZED ABSORPTION



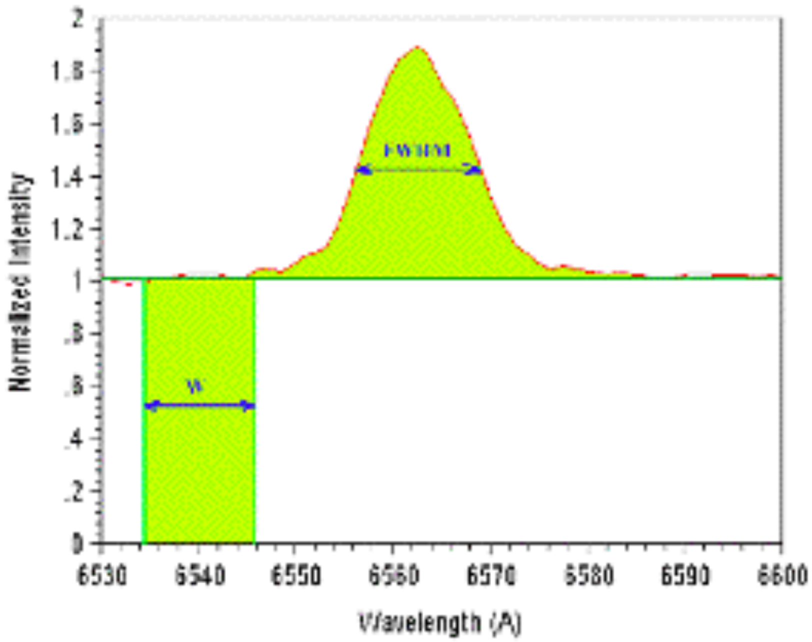
Continuum absorption profile still can be dominated by bound-free edges of abundant elements but….

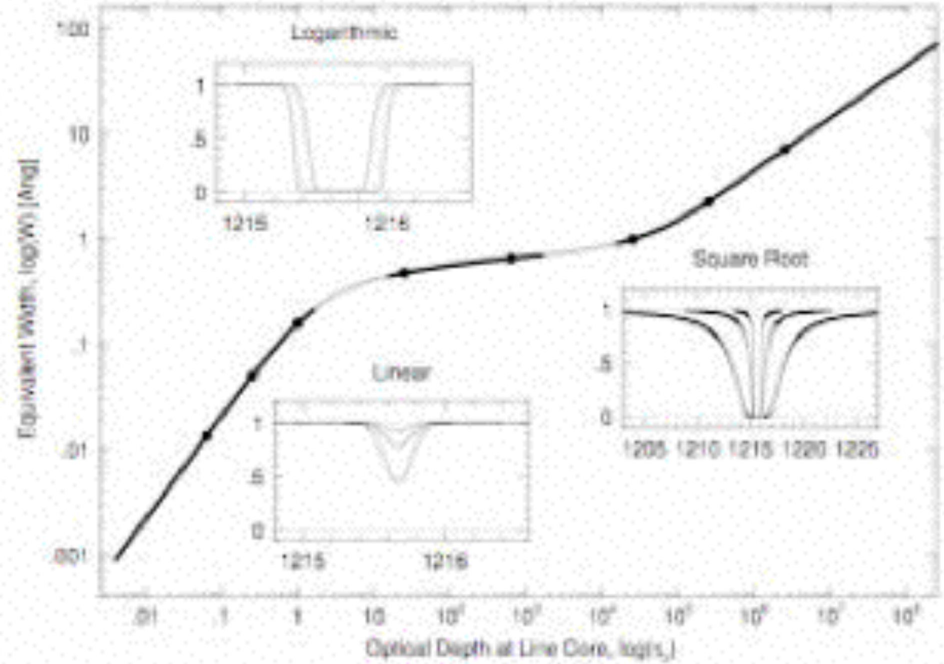
ABSORPTION LINES



- Absorption by a specific transition in atom
- Cross-sections larger than photoelectric
- But only over a small wavelength range
- Strength depends on Doppler parameter b
- Can measure N_H, U, velocity etc.

ABSORPTION LINES





Equivalent width:

$$EW = \frac{\int_{-\infty}^{\infty} F_l(E)dE}{F_c(E_l)}$$

$F_l =$ line flux, $F_c =$ continuum flux,

$E_l =$ line energy

Curve of growth:

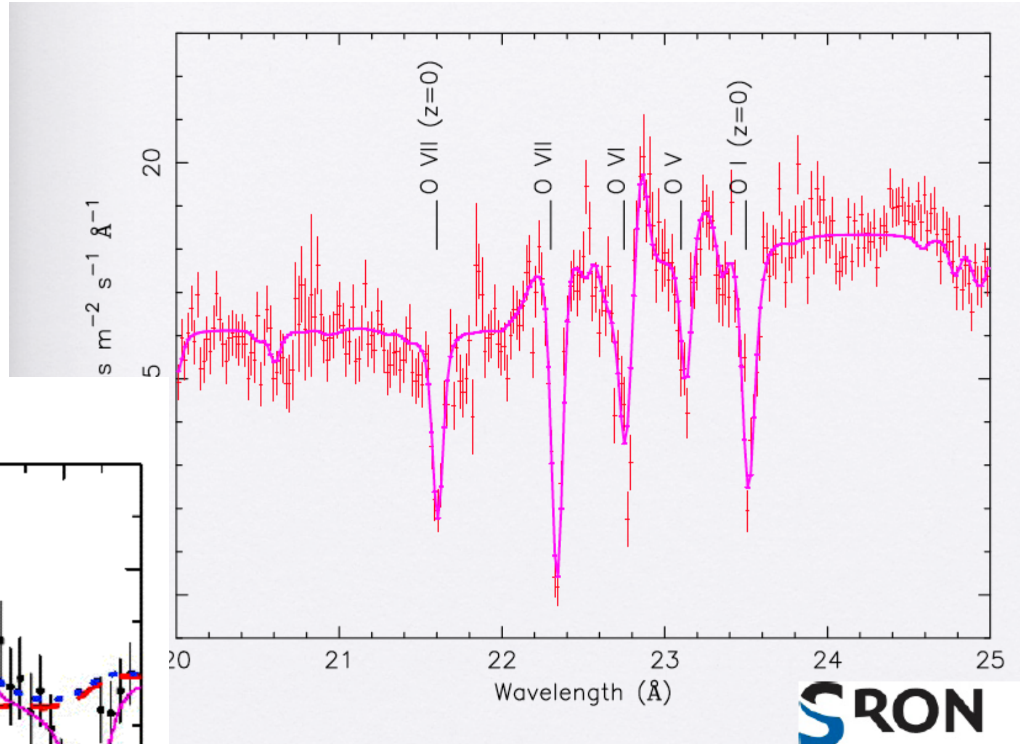
$\tau < 1 \quad EW \propto N$ (linear)

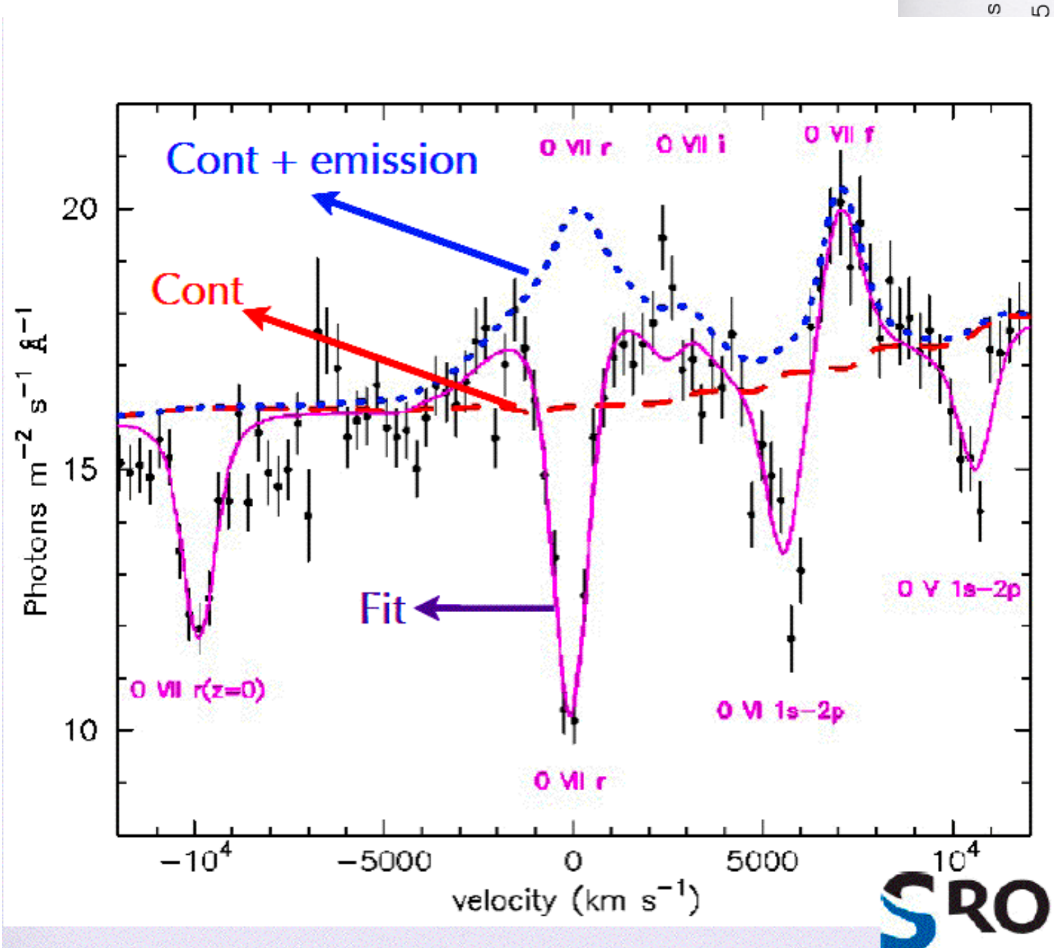
$10 < \tau < 10^3 \quad EW \approx const$ (saturated)

$\tau >> 10^4 \quad EW \propto \sqrt{N}$ (damping wings)

Examples of Emission and Absorption Lines

- Mkn509 - section of the x-ray spectrum
- Notice the wide range of ionization





Summary

- blackbody : everything hits everything, many times- equilibrium
- synchrotron : electrons bend in magnetic fields
- bremmstrahlung (free-free) : electrons bend in electric fields
- Compton scattering : photons hit electrons
- inverse Compton : photons hit energetic electrons
- free-bound : electrons hit atoms, get captured
- photoionization : photons hit atoms, electrons escape
- charge exchange : ions hit neutrals, swap electrons
- bound-bound : electrons jump down quantum levels

Next Lecture

- How are high energy photons detected?
  - X-ray imaging and spectroscopic detectors
  - γ-ray detectors
- X-ray telescopes