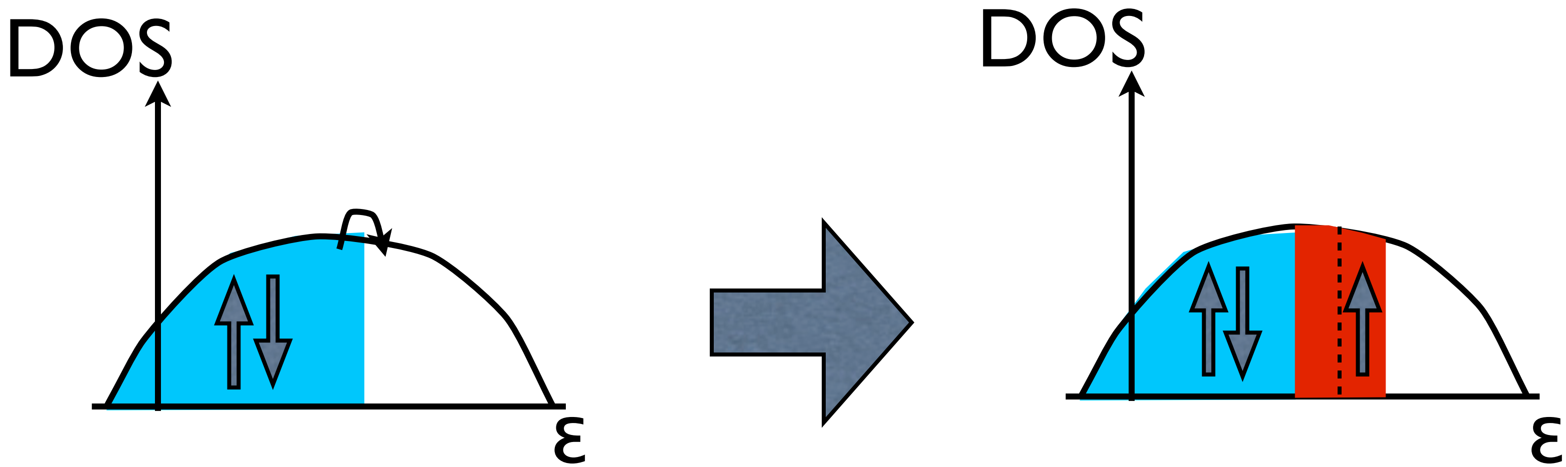
Magnetism

- Ferromagnetism has been known since ancient times, at least to the Greeks and Chinese
- Basic physics: electrons have spin S=1/2. Sometimes they align
- Much more common is *antiferromagnetism*: electron spins orient but in a way that adds up to zero net moment

Magnetism

- Mechanism?
  - Beyond band theory: for non-interacting electrons, it always costs energy to have spin polarization



  - Magnetism is *always* due to e-e interactions

Magnetism

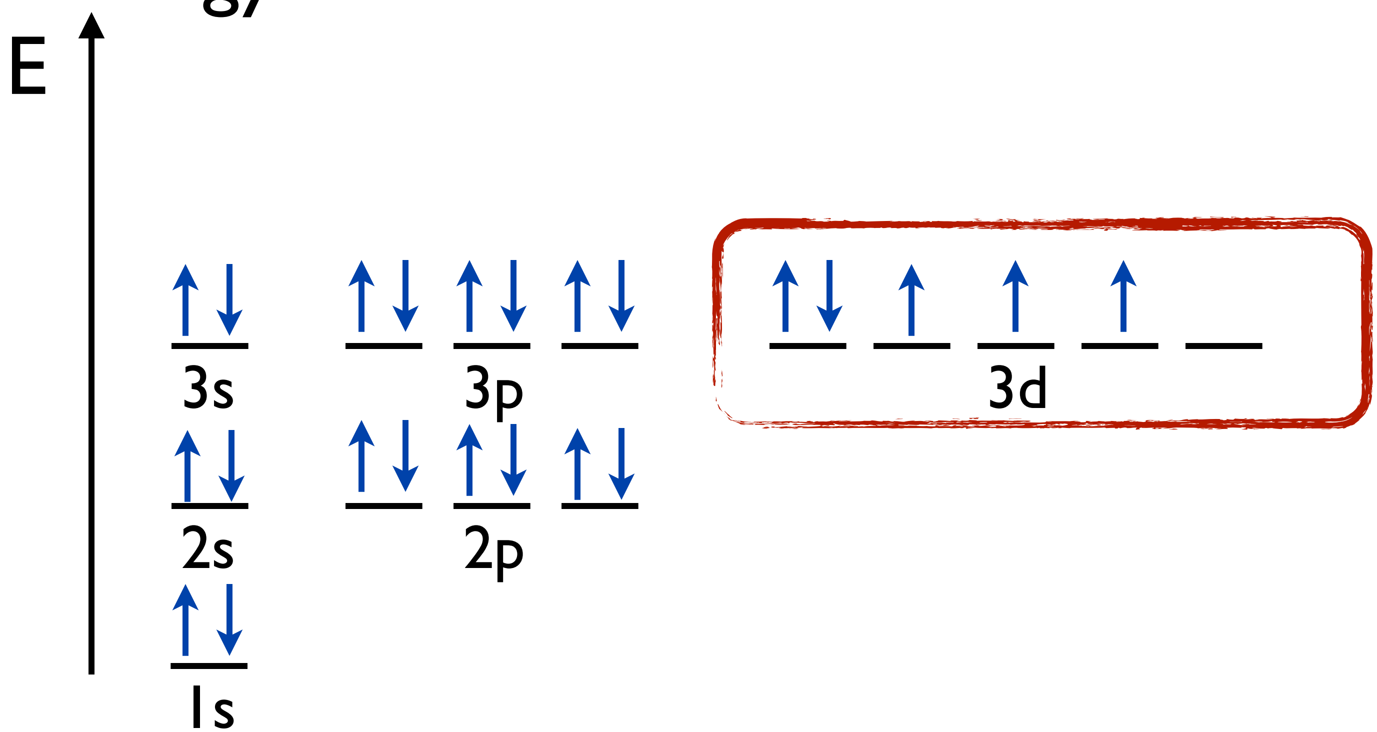
- So like superconductivity, magnetism is an effect of interactions between electrons
- But unlike superconductivity, magnetism requires *strong* interactions
  - Arbitrarily weak attraction leads to superconductivity, hence most metals become superconducting - but usually at quite low T
  - Few metals are magnetic. In fact, most antiferromagnets are insulating.
- Basic reason: interactions must overcome kinetic energy. Insulators have the least KE

Atomic magnetism

- Since magnetism requires small kinetic energy, it is strongest when electrons are approximately localized to atoms
  - Many "isolated" atoms are magnetic
  - Most magnetism has some atomic origins

Atomic magnetism

- Hydrogen atom $E_n = -\frac{\mathrm{Ry}}{n^2}$
- Level degeneracy: magnetism w/o kinetic energy cost



Atomic magnetism

- In principle, many-electron atom is a many-particle quantum problem

$$H = \sum_i -\frac{\hbar^2}{2m}\nabla_i^2 - \frac{Ze^2}{r_i} + \sum_{i>j}\frac{e^2}{r_{ij}} + H_{SOC}$$

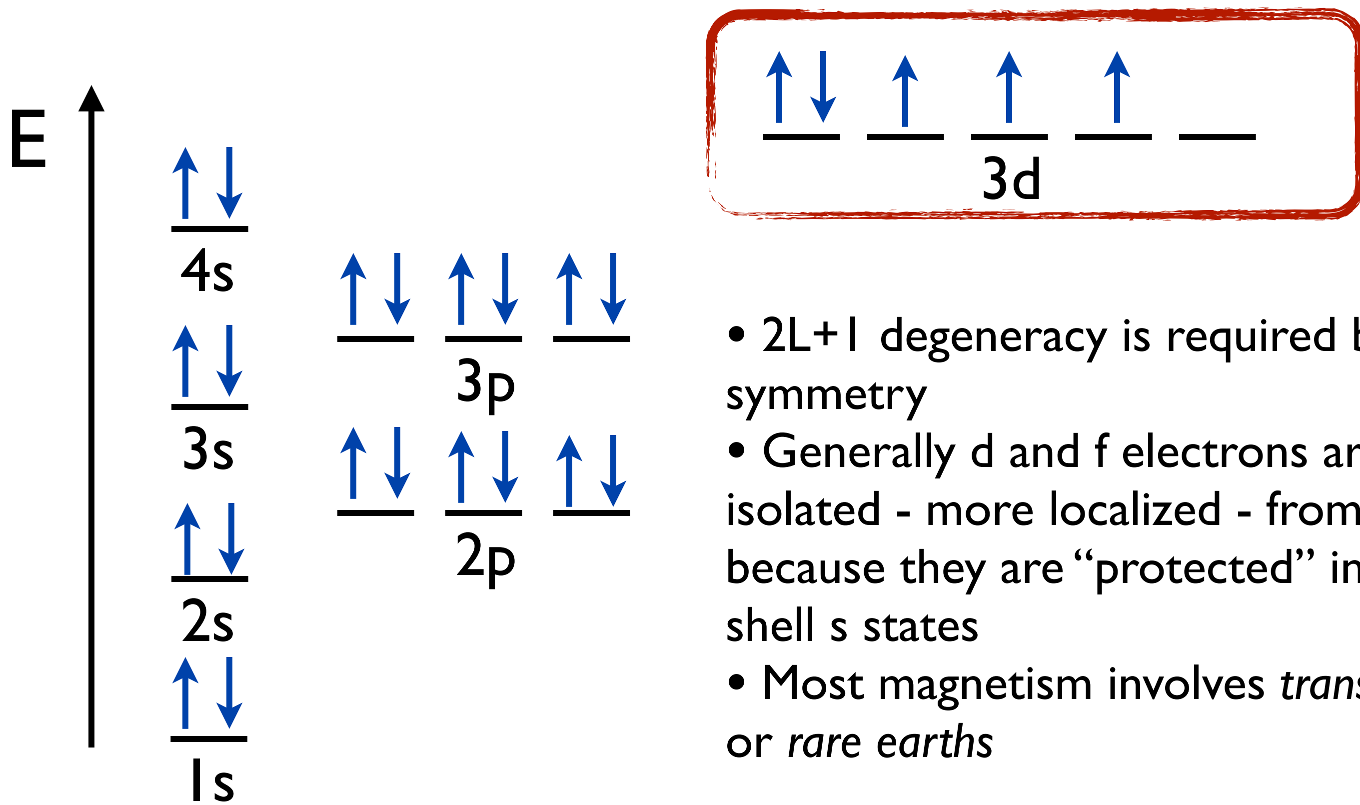
- This requires solving for an N-particle wavefunction

$$\Psi(\mathbf{r}_1, \cdots, \mathbf{r}_N; \sigma_1, \cdots, \sigma_N)$$

- Very hard and complex! We can get some intuition by thinking of 1-electron levels for the "outer" electrons only

Atomic magnetism

- In larger atoms, accidental degeneracy is lifted, and $E_{2s}<E_{2p}$, $E_{3s}<E_{3p}<E_{3d}$ etc



- 2L+1 degeneracy is required by spherical symmetry
- Generally d and f electrons are most isolated - more localized - from other atoms because they are "protected" inside higher shell s states
- Most magnetism involves *transition metals* or *rare earths*

Atomic magnetism

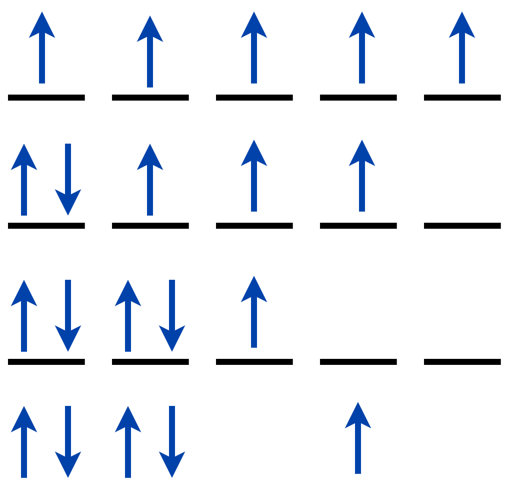
- A partially filled shell has a lot of possible states

S=5/2

S=3/2

S=1/2

S=1/2



etc.

- Without considering interactions *between* electrons in these shells, all are degenerate