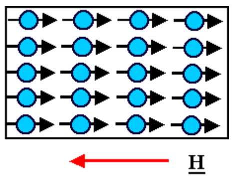
4.1.3 Classifications of Interactions and Types of Magnetism

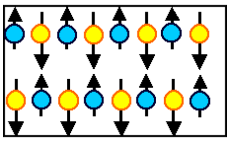
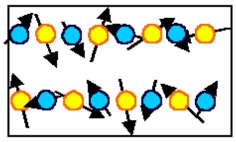
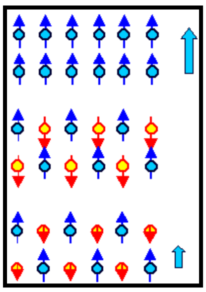
Dia-, Para-, and Ferromagnetism

- We want to get an idea of what happens to *materials* in external magnetic fields. "Material", in contrast to a single atom, means that we have plenty of (possibly different) atoms in close contact, i.e with some bonding. We can distinguish two basic cases:
  - **1.** The atoms of the material have *no magnetic moment* of their own. This is generally true for about one half of the elements; the ones with even atomic numbers and therefore an even number of electrons. The magnetic moments of the spins tends to cancel; the atoms will only have a magnetic moment if there is an orbital contribution. Of course, the situation may change if you look at *ions* in a crystal.
  - **2.** At least *some* of the atoms of the material have a magnetic moment. That covers the other half of the periodic table: All atoms with an odd number of electrons will have one spin moment left over. Again, the situation may be different if you look at ionic crystals.
- Lets see what can happen if you consider interactions of the magnetic moments with each other and with a magnetic field. First, we will treat the case of solids with *no magnetic moments* of their constituents, i.e. **diamagnetic materials**.
  - The following table lists the essentials

Diamagnetic Materials		
Magnetic moment?	No	
Internal magnetic interaction?	None	
Response to external field	Currents (and small magn. moments) are induced by turning on the field because the orbiting electrons are slightly disturbed. The induced magn. moments oppose the field. No temperature dependence Mechanism analogous to electronic polarisation in dielectrics,	 *The* black *arrows should be seen as being very short!!!!*
Value of μ_r	**$\mu_r \leq\approx 1$** in **diamagnetic** Small effect in "regular" materials	**$\mu_r = 0$** in **superconductors** (ideal diamagnet)
Value of *B*	$B \leq\approx \mu_0 \cdot H$	**$B = 0$** in superconductors
Typical materials	All elements with filled shells (always even atomic number)	all noble gases, H_2, Cu, H_2O, NaCl, Bi, ... Alkali or halogene *ions*

- Since you cannot expose material to a magnetic field without encountering a changing field strength **d*H*/d*t*** (either by turning on the field on or by moving the specimen into a field), currents will be induced that produce a magnetic field of their own.
  - According to **Lenz's law**, the direction of the current and thus the field is always such as to oppose the generating forces. Accordingly, the **induced magnetic moment** will be *antiparallel* to the external field.
  - This is called **diamagnetism** and it is a weak effect in normal materials.
- There is an exception, however: **Superconductors**, i.e. materials with a **resistivity = 0** at low temperatures, will have their mobile charges responding without "resistance" to the external field and the induced magnetic moments will *exactly cancel* the external field.
  - Superconductors (at least the "normal" ones (or "type **I**" as they are called) therefore are always *perfectly field free* - a magnetic field cannot penetrate the superconducting material.
  - That is just as amazing as the zero resistance; in fact the magnetic properties of superconductors are just as characteristic for the superconducting state of matter as the resistive properties.

- There will be a backbone II module for superconductors in due time
- If we now look at materials where at least *some of the atoms* carry a permanent magnetic moment, we have to look first at the possible *internal interactions* of the magnetic moments in the material and then at their interaction with an *external field*. Two limiting cases can be distinguished.
  - **1.** Strong internal interaction (i.e. interaction energies **»** **k*T***, the thermal energy). **Ferromagnetism** results
  - **2.** No or weak interaction. We have **paramagnetic materials**.
- The first case of strong interaction will more or less turn into the second case at temperatures high enough so that **k*T* >>** interaction energy, so we expect a temperature dependence of possible effects. A first classification looks like this:

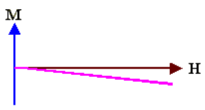
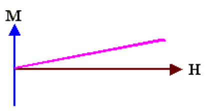
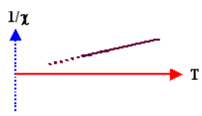
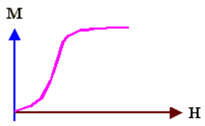
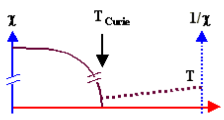
Paramagnetic and Ferromagnetic Materials		
Magnetic moment?	Yes	
Internal agnetic interaction?	Strong	Weak
Ordered regions?	Yes	No
	 This example shows a **ferrimagnetic material** Ordered magnetic structures that are stable in time. Permanent magnetization is obtained by the (vector) sum over the individual magnetic moments.	 Example for a **paramagnetic material** Unordered magnetic structure, fluctuating in time. Averaging over time yields no permanent magnetization
Response to external field	A large component of the magnetic moment may be in field direction	Small average orientation in field direction. Mechanism *fully* analogous to orientation polarization for dielectrics
Kinds of ordering	Many possibilities. Most common are *ferro*-, *antiferro*-, and *ferri*magnetism as in the self-explaining sequence below: 	
Value of μ_r	**μ_r >> 1** for ferromagnets **$\mu_r \approx 1$** for anti-ferromagnets **$\mu_r > 1$** for ferrimagnets	**$\mu_r \geq\approx 1$**
***T*-dependence**	Paramagnetic above **Curie Temperature**	Weak ***T***-dependence
Paramagnetic materials (at room temperature)		Mn, Al, Pt, O_2(gas and liquid), rare earth ions, ...

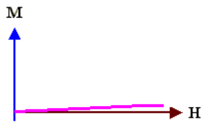
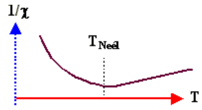
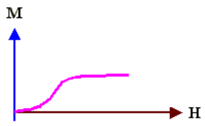
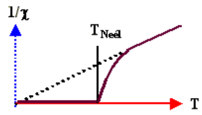
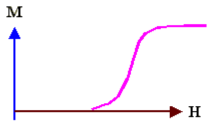
Ferromagnetic materials (with Curie- (or Neél) ***T***)	Ferro elements: Ferro technical: Ferri: Antiferro: (no technical uses)	Fe (770 ^0C), Co (1121 ^0C), Ni (358 ^0C), Gd (16 ^0C) "AlNiCo", Co_5Sm, $Co_{17}Sm_2$, "NdFeB" Fe_3O_4, MnO (116 ^0C), NiO (525 ^0C), Cr (308 ^0C)

- This table generated a lot of new names, definitions and question. It sets the stage for the dealing with the various aspects of *ferromagnetism* (including *ferri*- and *anti-ferro* magnetism as well as some more kinds of internal magnetic ordering. A few examples of ferromagnetic materials are given in the link.
  - There might be *many more types* of ordering: Any fixed relation between two vectors qualify. As an example, moment **2** might not be parallel to moment **1** but off by ***x*** degrees; and the succession of many moments might form a spiral pattern.
  - If you can think of some possible ordering (and it is not forbidden by some overruling law of nature), it is a safe bet that mother nature has already made it in some exotic substance. But, to quote Richard **Feynman**:
  - *"It is interesting to try to analyze what happens when a field is applied to such a spiral* (of magnetic ordering) *- all the twistings and turnings that must go on in all those atomic magnets. (Some people like to amuse themselves with the theory of these things!)"* (Lectures on Physics, Vol **II**, **37-13**; Feynmans emphasizes).
- Well, we don't, and just take notice of the fact that there is *some* kind of magnetic ordering for *some* materials.
  - As far as the element are concerned, the only ferromagnets are: **Fe**, **Ni**, and **Co**. (**Mn** almost is one, but not quite).
  - Examples for antiferromagnets include **Cr**, ...
  - And there are many, many *compounds*, often quite strange mixtures (e.g. **NdFeB** or $\mathbf{Sm_2Co_{17}}$), with *remarkable and often useful* ferro-, ferri, antiferro, or,..., properties.

Temperature Dependence of Magnetic Behavior

- How do we distinguish an *antiferromagnetic* material from a *paramagnet* or a *diamagnet*? They all appear not to be very "magnetic" if you probe them with a magnetic field.
  - We have to look at their behavior in a magnetic field *and* at the *temperature dependence* of that behavior. Ordering the atomic magnetic moments is, after all, a *thermodynamical effect* - it always has to compete with entropy - and thus should show some specific temperature dependence.
  - There are indeed quite characteristic curves of major properties with temperature as shown below.

Magnetization ***M* = *M*(*H*)**	**Magnetic susceptibility** $\chi_{mag} = \chi_{mag}(T)$	**Remarks**
		For **diamagnets** the susceptibility is negative and close to zero; and there is no temperature dependence.
		For **paramagnets**, the susceptibility is (barely) larger than zero and decreases with ***T***. Plotted as **1/χ(*T*)** we find a *linear* relationship.
		For **ferromagnets** the susceptibility is large; the magnetization increases massively with **H**. Above a critical temperature $\mathbf{T_{Cu}}$, the *Curie temperature*, paramagnetic behavior is observed.

		**Antiferromagnets** are like paramagnets *above* a critical temperature T_{Ne} called **Neél temperature**. Below T_{Ne} the susceptibility is small, but with a ***T***-dependence quite different from paramagnets.
		**Ferrimagnets** behave pretty much like *ferro*magnets, except that the effect tends to be smaller. The **1/**χ**(*T*)** curve is very close to zero *below* a critical temperature, also called Neél temperature.
	Just for good measure, the behaviour of one of the more exotic magnetic materials. Shown is a **metamagnet**, behaving like a *ferro* magnet, but only *above* a critical magnetic field strength.	

- The question now will be if we can understand at least *some* of these observations within the framework of some simple theory, similar to what we did for dielectric materials
  - The answer is: *Yes*, we can - but only for the rather uninteresting (for engineering or applications) *dia*- and *para*magnets.
  - Ferro magnets, however, while *extremely interesting electronic materials* (try to imagine a world without them), are a different matter. A real understanding would need plenty of quantum theory (and has not even been fully achieved yet); it is far outside the scope of this lecture course. But a phenomenological theory, based on some assumptions that we do not try to justify, will come straight out from the theory of the orientation polarization for dielectrics, and that is what we are going to look at in the next subchapters.

Questionaire
Multiple Choice questions to 4.1.3