Rare Earth Materials [Canfield]

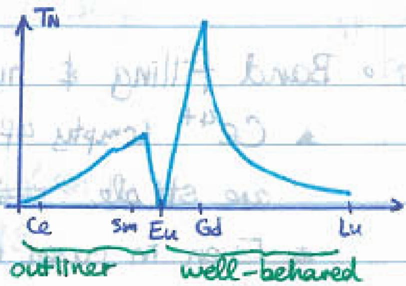
- Rare earth are actually abundunt. But hard to get high purity.

Sc
Y
Lu
La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb

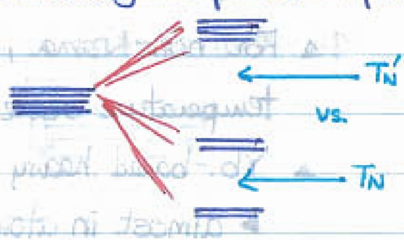
- Parameters tunable: size of unit cell, size of local moment/coupling, size/direction of anisotropy, entropy at low T, band filling, hybridization
  - ▲ The tuning is smooth & small, more controlable (c.f. transition metal)

- If one member in rare earth fit in compound, several may do. Since the 4f's are shielded & not participate in bonding
  - ▲ For $R^{3+}XY$, unit cell size generally decreases, with some exceptions. (known as lanthanide contraction)
  - ▲ Analogous to pressure tuning. e.g. $R\,Fe\,As\,(O_{1-x}F_x)$

- Magnetism is also tuned across series
  - ▲ de Genne scaling works well for heavier rare earths.
  - ▲ Gd can be used as a good first test on magnetic ordering.



- Direction/size of anisotropy & entropy at low-T.
  - ▲ Gd^{3+} & Eu^{2+} has $L=0$, thus crystal field (CEF) spliting is small ⇒ almost isotropic ⇒ good candidate for Heisenberg model
  - ▲ Most rare earths have $L \neq 0$. Ordering temp T_N important in determine remenant entropy:
    - ⇒ induce anisotropy, in many case Ising.



- For $HoNi_2B_2C$, CEF confines moment to basal plane, specifically, to a 4-state clock model
  - A suprise, since non-Ising anisotropy suggests XY-order
  - Similar example in $DyAgSb_2$
  - This give rise to rich phase diagram.
  - Allow creation of non-Heisenberg spin spinglass.
    - Not "random" spinglass but "aperiodic" spinglass, since it is possible to get quasicrystal without titration.

- The series also differ by whether there is Kramer (ground state 2-fold) degeneracy or not
  Ce Pr Nd Pm ... / Kramer / non-Kramer

- Band filling & hybridization (& also Kondo effect)
  - Ce^{4+} (empty 4f), Yb^{2+} (fully 4f), & Ed^{2+} (½-filled 4f) are stable ⟹ deviation from usual R^{3+} state.
  - Even in cases where these are not stable at room temperature (i.e. there're in R^{3+} at room temperature), the 4f band can hybtridize at low T, leading to Kondo physics.
  - For Kramer's ions, the 2-fold $H=0$ degeneracy can be removed by hybirdizing & forming heavy fermion (or more modernly by magnetic ordering). This make them good Kondo candidates.
  - For non-Kramer, it is still possible that entropy remains temperature scale for hybirdization... e.g. $PrAg_2In$
  - Yb-based heavy fermion (new): YbT_2Zn_{20}
    - almost in atomic limit. Yb are very dilute.
- For T_K, T_N close, rare earths tuning allows swaping through QCP.