Happy new year!

14. Repetition

- Explain the photoelectric effect. In which photon energy range can it be observed?
- Explain the principle of ARPES. How can we retrieve information about the electronic dispersion?
- Give a few examples of continuous phase transitions.
- What determines the order of a phase transition in Ehrenfest and in Landau´s pictures, respectively?

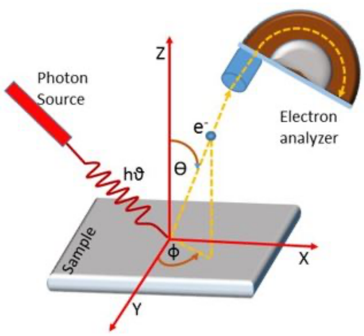
15. Dirac Cone in Graphene and photoemission

Graphene is a two-dimensional material that consists of a monoatomic layer of Carbon atoms arranged in a 2D honeycomb lattice (cf. Pb 2 in tutorial #1). Lattice constant a is 2.4 Å.

It can be shown that the dispersion relation for the $2p_z$-derived band in graphene has the following dispersion relation (E_F is set to 0 here):

$$E(k_x, k_y) = \pm t_{pp}\sqrt{1 + 4cos\left(\frac{3ak_x}{2}\right)cos\left(\frac{\sqrt{3}ak_y}{2}\right) + 4cos^2\left(\frac{\sqrt{3}ak_y}{2}\right)}$$

1) Represent the real space unit cell and first Brillouin zone for Graphene. How does the Fermi surface look like?
2) Show that for wave vector $k = k_0 + q$, where k_0 is a corner of the Brillouin zone, (also referred to as K-point) we can write: $E(k_x, k_y) = \pm t_{pp}\frac{3a}{2}|q|$. Sketch the dispersion.
3) For a photon energy of 100 eV, evaluate the polar and azimuthal angles θ and ϕ (see figure below) which are needed to determine the wave vectors for 6 different states around one of the K points (use the high symmetry directions) which have a constant binding energy E_B = 1eV (knowing that the Fermi velocity is 8×10^5 m/s) and that the work function into the spectrometer is Φ = 4.5 eV.



16. Arrott-plot Method

Landau theory of a ferromagnet in a magnetic field B states that the free energy is given by

$$F(M) = F_0 + a(T - T_c)M^2 + bM^4 - MB$$

Where a and b positive constants.

a) Show that we can write $M^2 = u + v\frac{B}{M}$, where u and v are constants.

b) Explain how this can be used to determine the critical temperature T_c by plotting M^2 vs $\frac{B}{M}$ for temperature above, below and right at T_c. This method is known as the Arrott-plot method.

c) A ferromagnetic transition has been detected in the heavy-electron compound URu2Si2 doped with Re or Tc. Use the Arrott-plot method to determine the transition temperature T_c based on the data shown in the figure below (taken from Phys. Rev. B 39, 2423 (1989)) for two of these compounds.

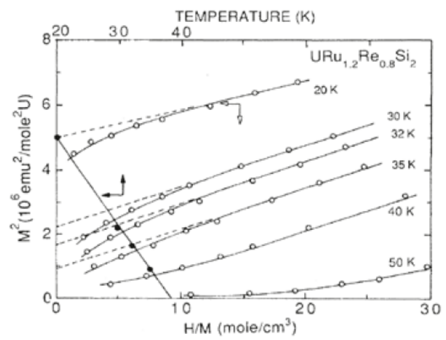


FIG. 4. Isotherms of M^2 vs H/M, where M is the magnetization and H is the applied magnetic field, for $URu_{1.2}Re_{0.8}Si_2$ for $20\ K \le T \le 50\ K$. Zero-field values of M^2, obtained by linear extrapolation of the high-field M^2 vs H/M data to $H=0$ (dashed lines), are plotted vs T. The Curie temperature Θ_C is defined as the temperature corresponding to $M^2=0$. Solid lines are guides to the eye.

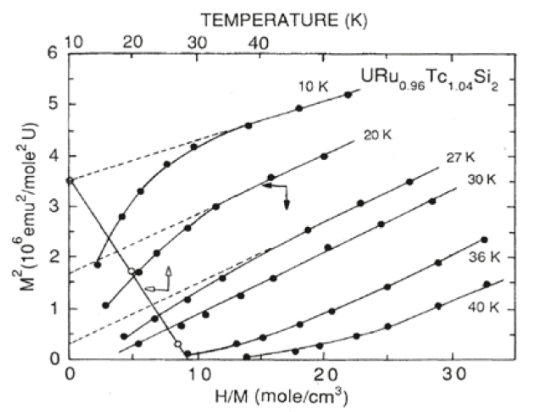


FIG. 5. Isotherms of M^2 vs H/M, where M is the magnetization and H is the applied magnetic field, for $URu_{0.96}Tc_{1.04}Si_2$ for $10\ K \le T \le 40\ K$. Zero-field values of M^2, obtained by linear extrapolation of the high-field M^2 vs H/M data to $H=0$ (dashed lines), are plotted vs T. The Curie temperature Θ_C is defined as the temperature corresponding to $M^2=0$. Solid lines are guides to the eye.