Lectures:

Monday, 29.4.: Review. Phonon specific heat, structure factor.
Thursday, 2.5.: Neutron scattering, anharmonic effects.
Monday, 6.5.: Electron wavefunction and "second quantization".

Exercises: to be handed in by **Tue. 14.5.** noon in box on 5th floor of Building 46 or electronically to laschwar@rptu.de

4) In the lecture it was claimed that for thermal expectation values of an arbitrary linear combination of bosonic operators $F=\sum_{\alpha,\vec{k}}\left(f_{\alpha,\vec{k}}a_{\alpha,\vec{k}}+g_{\alpha,\vec{k}}a^{\dagger}_{\alpha,\vec{k}}\right)$ the following equality holds: $\left\langle e^{F}\right\rangle=e^{\left\langle F^2/2\right\rangle}$.

a) Show this equality for a single oscillator mode $F=f\,a+g\,a^{\dagger}$ for $T=0$ (ground state expectation).

b) Evaluate $e^{\left\langle F^2/2\right\rangle}$ in terms of f and g for the finite temperature case.

c) Argue that $\left\langle e^{F}\right\rangle=e^{\left\langle F^2/2\right\rangle}$ is valid for any number of phonon modes if they are independent and express $\left\langle F^2/2\right\rangle$ as a sum over the 1BZ.

5.) Consider the Debye-Waller factor e^{-2W} with $2W=\left\langle(\vec{q}\cdot\vec{X}_j)^2\right\rangle$.

a) Evaluate $2W=\left\langle(\vec{q}\cdot\vec{X}_j)^2\right\rangle$ explicitly by inserting the expression of $\vec{X}_j$ in terms of normal phonon modes (see lecture 2-10). The final results should correspond to a sum over the 1BZ.

b) The Debye approximation replaces the sum over the 1BZ by an integral over the sphere $k<k_D$ and assumes a constant velocity independent of direction $\alpha=x,y,z$. Use this approximation to simplify the expression for $2W=\left\langle(\vec{q}\cdot\vec{X}_j)^2\right\rangle$. Find an analytic expression for the integral for the low and the high temperature behavior as a function of T/T_D.