

Modelový prístup k magnetizmu v pevných látkach

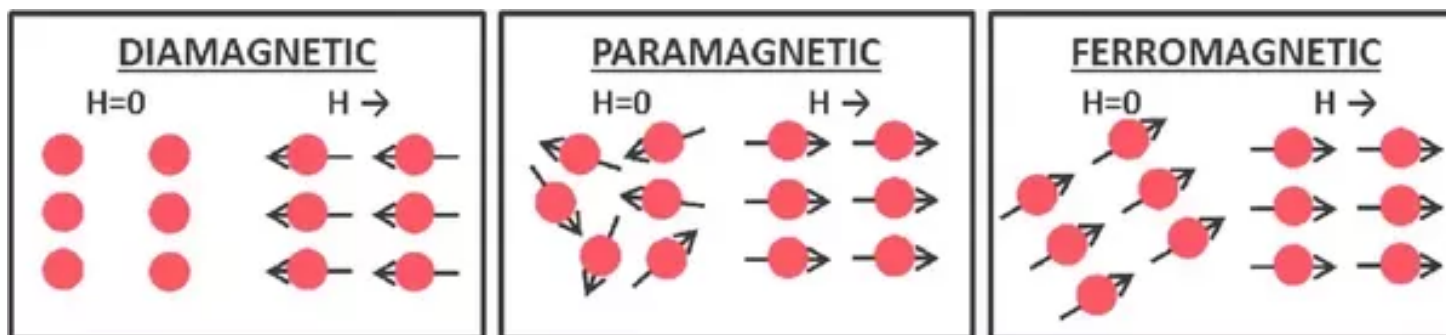
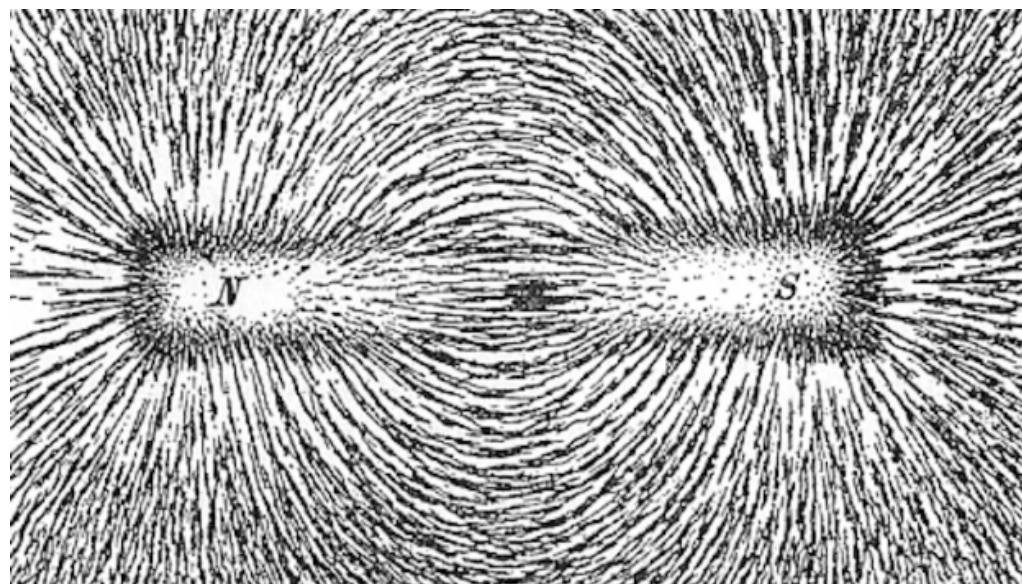
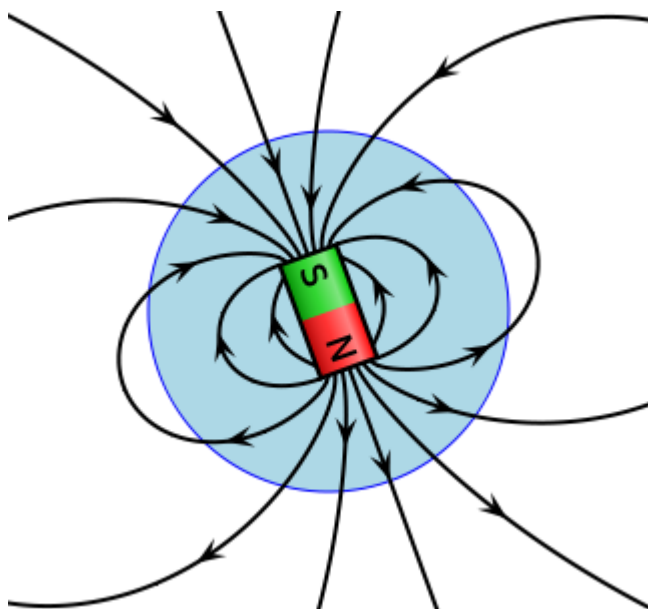
Juraj Rusnačko

1. Úvod - od materiálov k efektívnym modelom

2. Isingov model

3. Príklady z výskumu

Magnetizmus polí a látok



Etymológia magnetizmu

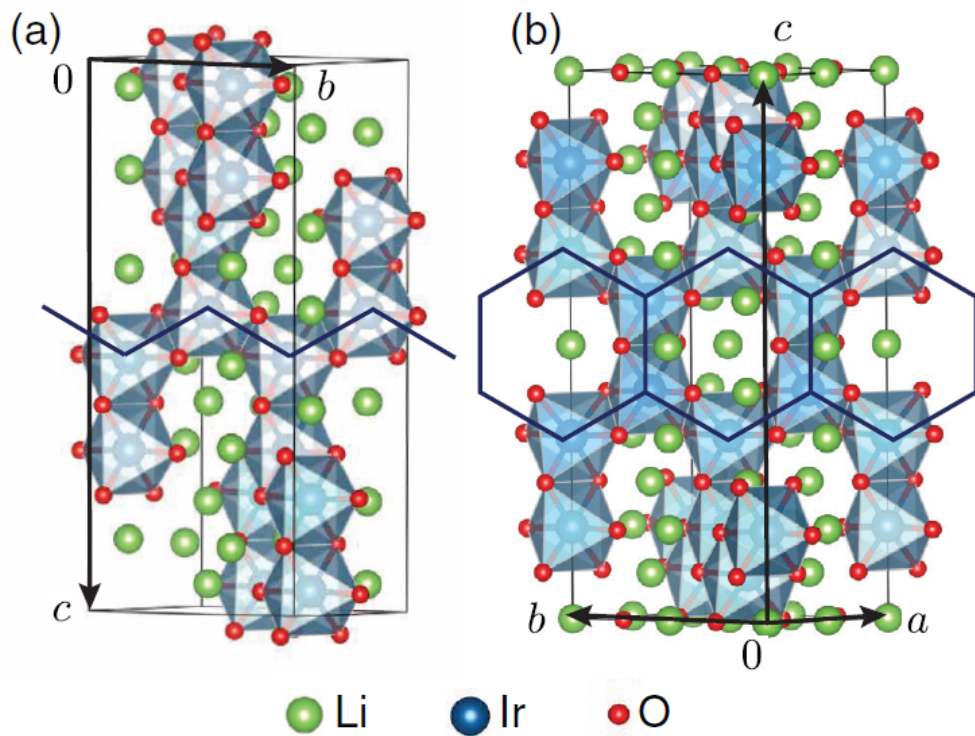
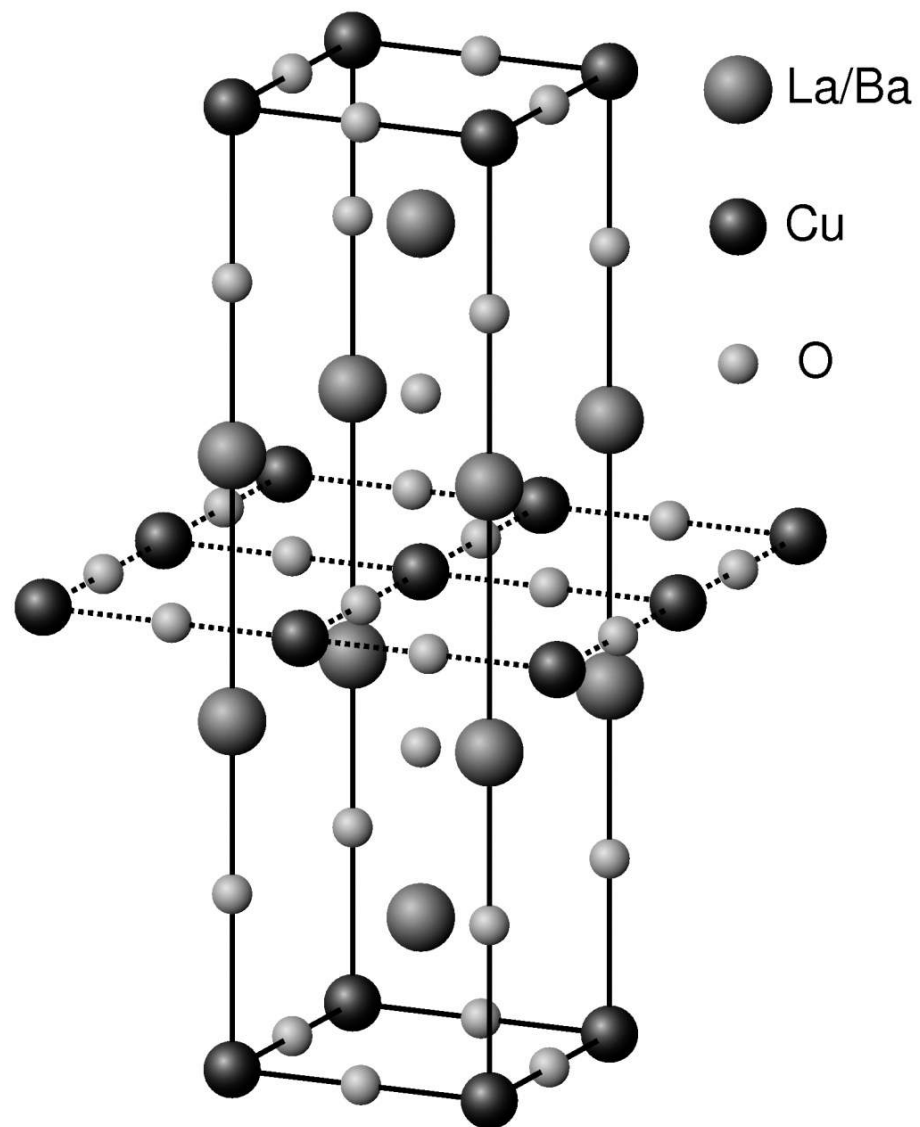
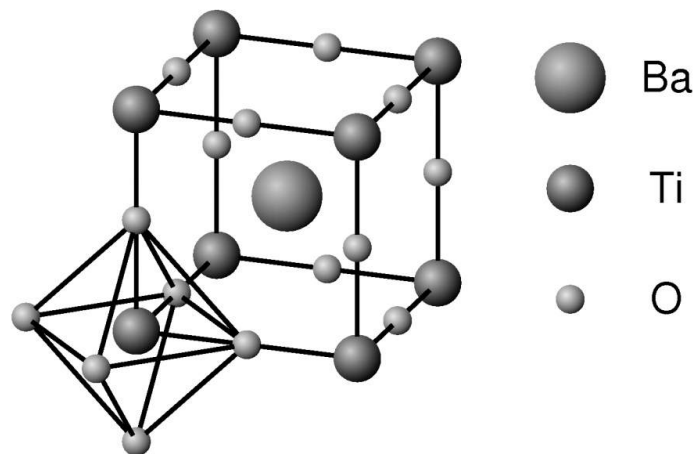
Magnetismus

☞

Magnetismus je fyzikální jev projevující se primárně silovým působením na pohybující se nositele elektrického náboje (nabité částice). Důsledkem tohoto působení jsou např. silové působení na (i nenabitá) tělesa (nejsilnější u feromagnetických látek) či změny elektrických, optických a dalších materiálových a termodynamických charakteristik látek vystavených magnetickému působení. Slovo magnetismus pochází z řeckého magnētis, což znamená magnetický (podle krajiny Magnésia v Thesálii v severovýchodním Řecku, kde byla naleziště rud s přírodním magnetismem).



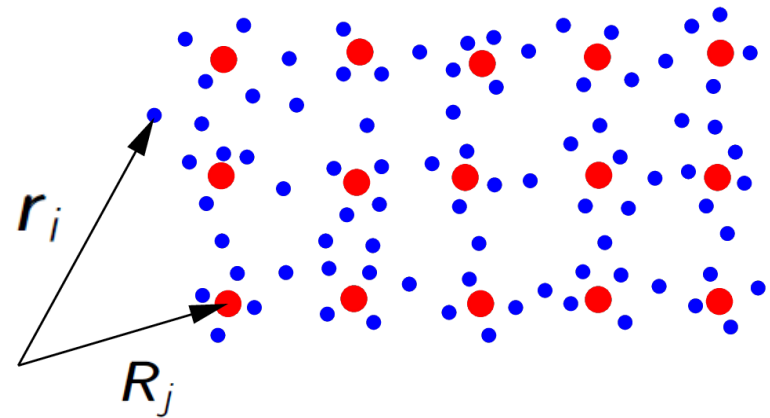
Kryštalové štruktúry



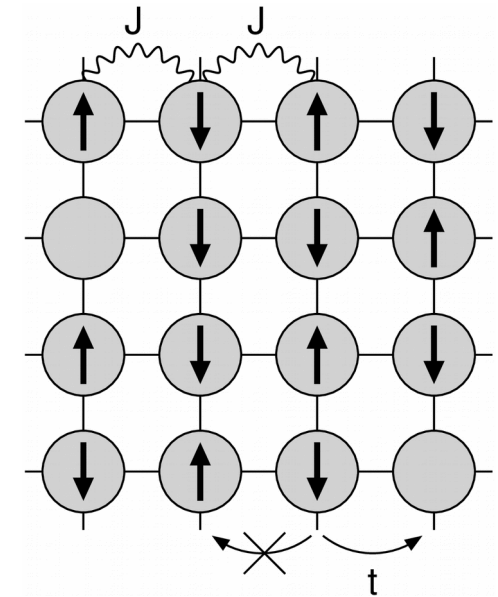
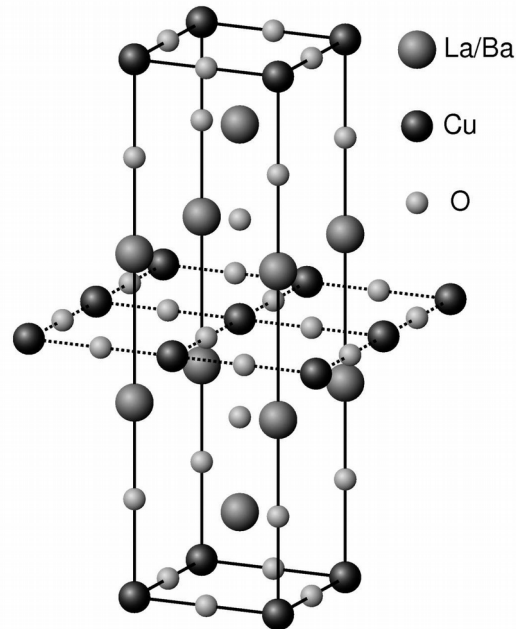
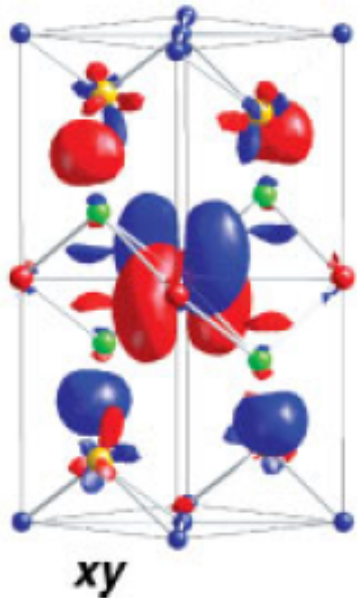
Mnohočasticový problém

$$\hat{\mathcal{H}} = \underbrace{\sum_i \frac{-\nabla_{\mathbf{r}_i}^2}{2m}}_{\hat{T}_e} + \underbrace{\sum_{i < i'} \frac{e^2}{|\hat{\mathbf{r}}_i - \hat{\mathbf{r}}_{i'}|}}_{\hat{V}_{e-e}} + \underbrace{\sum_j \frac{-\nabla_{\mathbf{R}_j}^2}{2M_j}}_{\hat{T}_j} + \underbrace{\sum_{j < j'} \frac{Z_j Z_{j'} e^2}{|\hat{\mathbf{R}}_j - \hat{\mathbf{R}}_{j'}|}}_{\hat{V}_{j-j}} + \underbrace{\sum_{ij} \frac{Z_j e^2}{|\hat{\mathbf{r}}_i - \hat{\mathbf{R}}_j|}}_{\hat{V}_{e-j}}$$

$$\Psi(\mathbf{r}_1, \mathbf{r}_2, \dots, \mathbf{r}_N, \mathbf{R}_1, \mathbf{R}_2, \dots)$$



Efektívny model



Osnova

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2. Isingov model

3. Príklady z výskumu

Isingov model

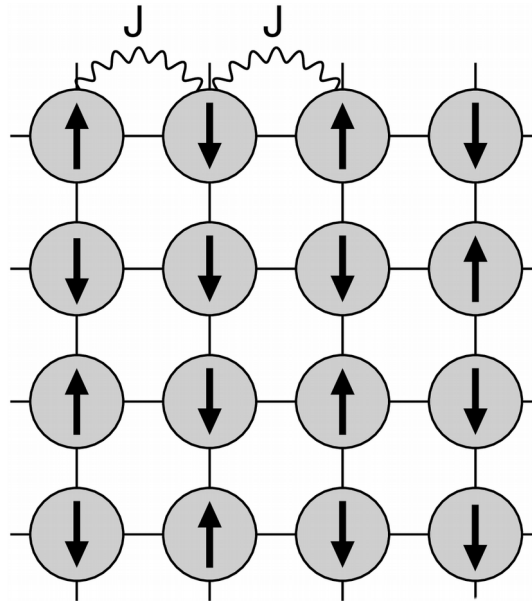
- prvý model obsahujúci spojitý fázový prechod

$$E = -J \sum_{\langle ij \rangle} \sigma_i \sigma_j, \quad \sigma \in \{+1, -1\}$$

- na konečnej teplote:

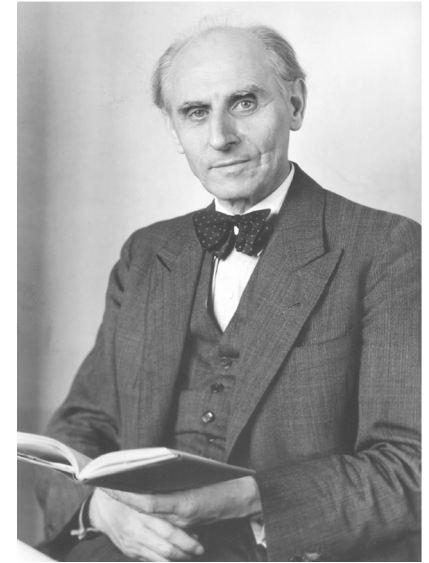
$$p(T, \{\sigma\}) = \frac{e^{-E(\{\sigma\})/kT}}{Z(T)},$$

$$Z(T) = \sum_{\sigma_1} \dots \sum_{\sigma_N} e^{-E(\{\sigma_i\})/kT}$$

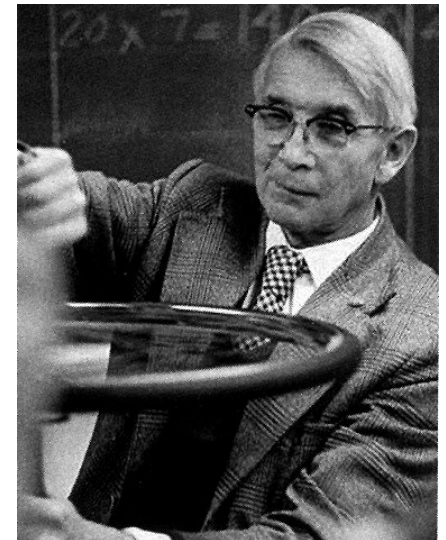


- na nulovej teplote feromagnet, na T_c prechod do paramag. stavu

$$F = E - TS$$



Wilhelm Lenz



Ernst Ising

Onsagerovo analytické riešenie (1944)

- jeden z mílnikov teoretickej fyziky 20. storočia
- exaktné riešenie v 2D, bez externého magnetického poľa

$$\begin{aligned} -F/NkT = \log \lambda = & \frac{1}{2} \log(2 \sinh 2H) \\ & + \frac{K}{\pi} \int_0^a \Phi(iu) du = y \log(2 \sinh 2H') \\ & + (\frac{1}{2} - y) \log(2 \sinh 2H) + 2 \int_0^y \log \cot(\pi z) dz \\ & + \frac{1}{\pi} \sum_{n=0}^{\infty} \frac{(1 + (4n+2)(\pi i/\tau) - \exp[-(4n+2)\pi i/\tau])}{(2n+1)^2 \sinh^2((2n+1)\pi i/\tau)} \\ & \quad \times \sin((4n+2)\pi y). \quad (7.6) \end{aligned}$$



Lars Onsager

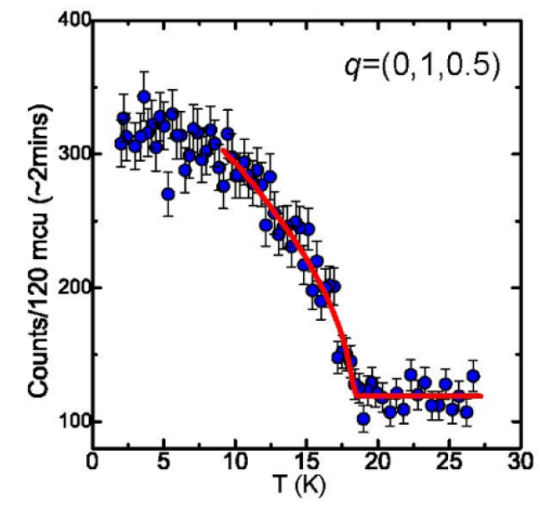
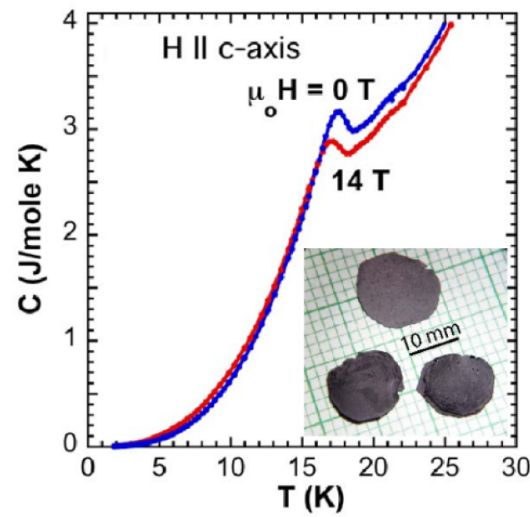
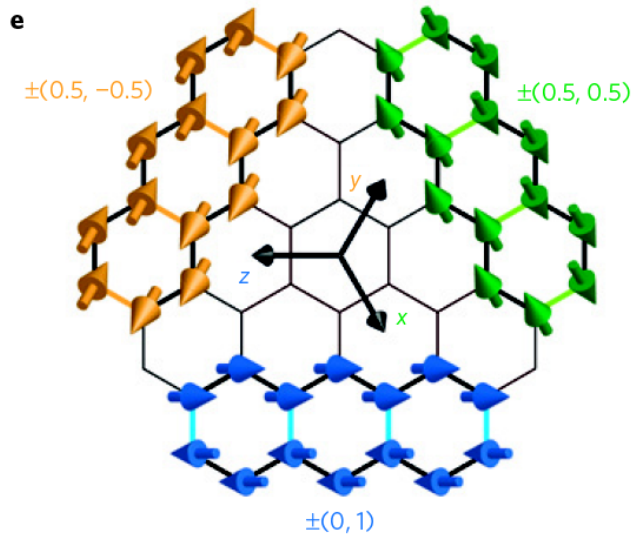
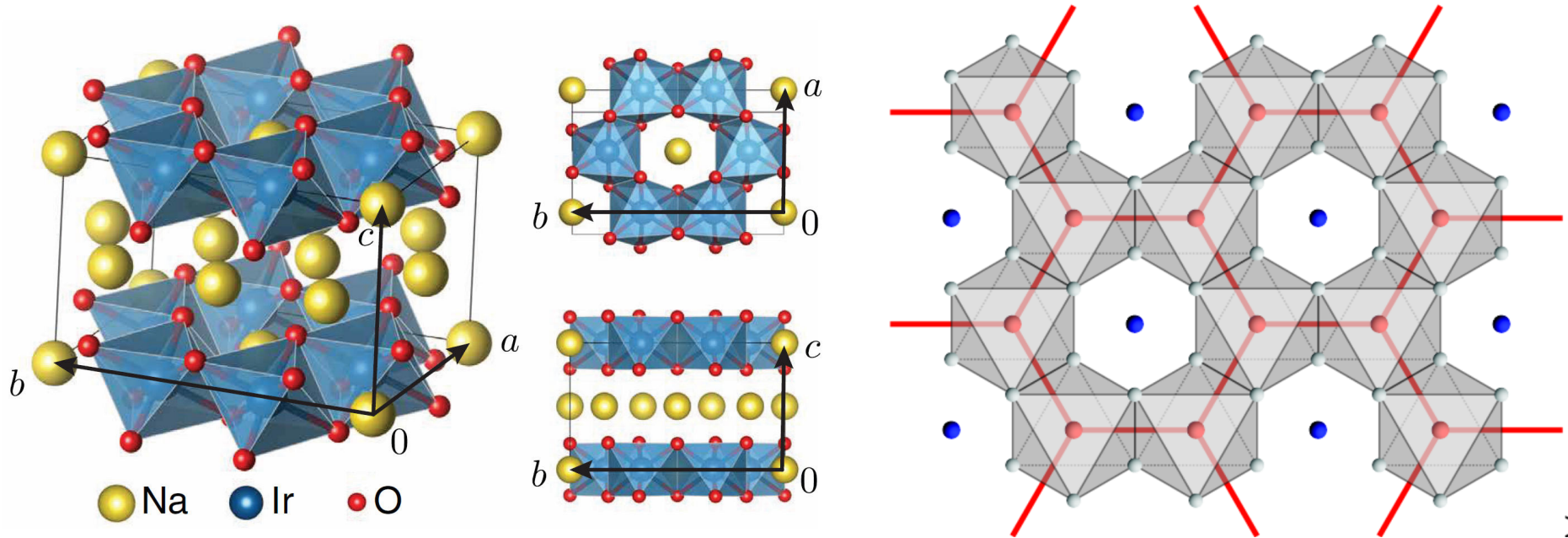
$$-\beta f = \ln 2 + \frac{1}{8\pi^2} \int_0^{2\pi} d\theta_1 \int_0^{2\pi} d\theta_2 \ln[\cosh(2\beta J_1) \cosh(2\beta J_2) - \sinh(2\beta J_1) \cos(\theta_1) - \sinh(2\beta J_2) \cos(\theta_2)].$$

- matematika z Appendixu: theta funkcie, Jacobiho eliptické funkcie, eliptické integrály 1., 2. a 3. druhu, kvaternióny, gudermannian, Landonova transformácia, ...

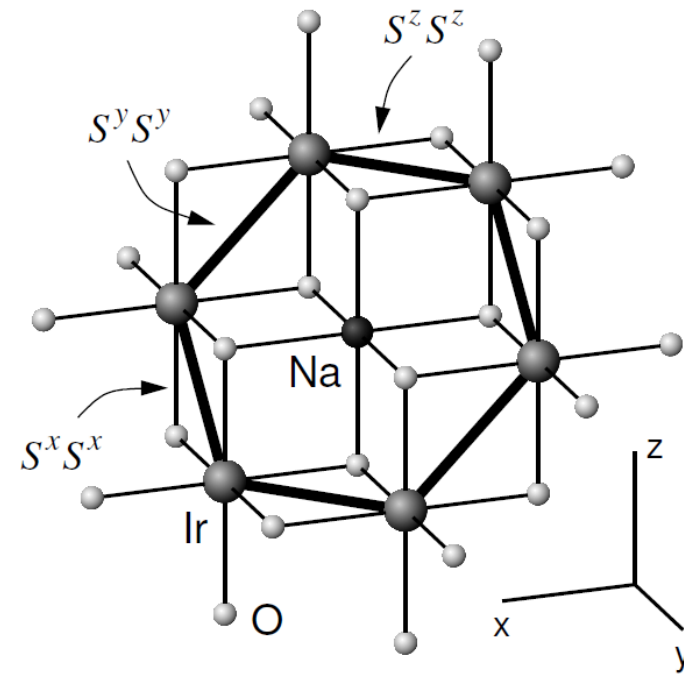
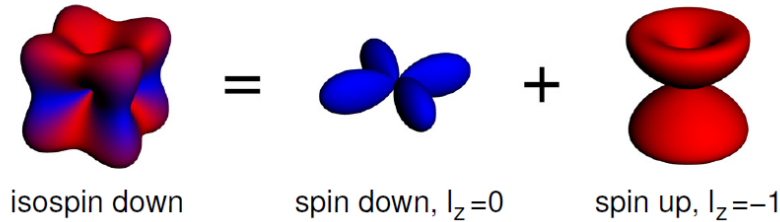
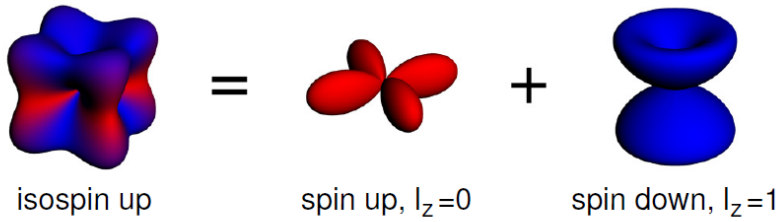
Osnova

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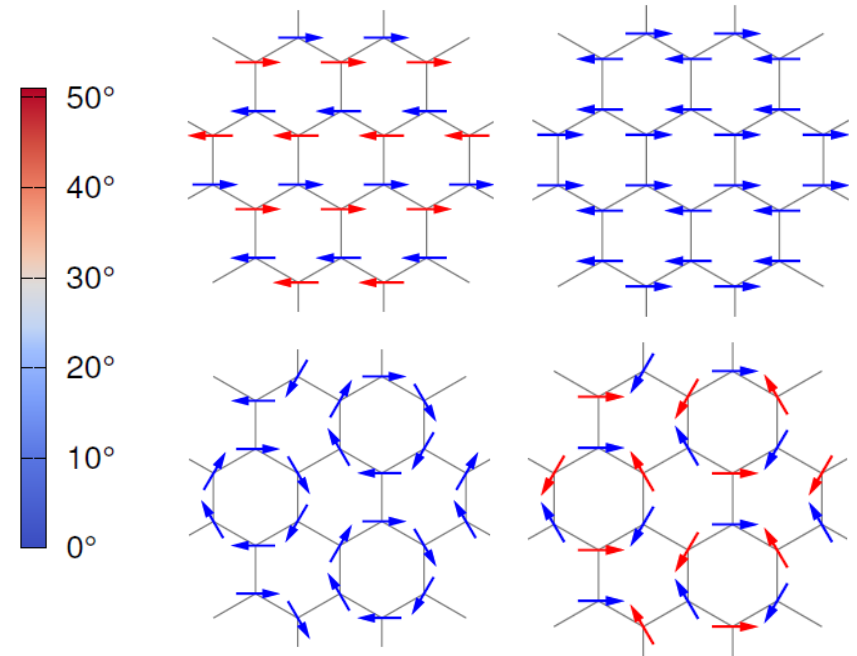
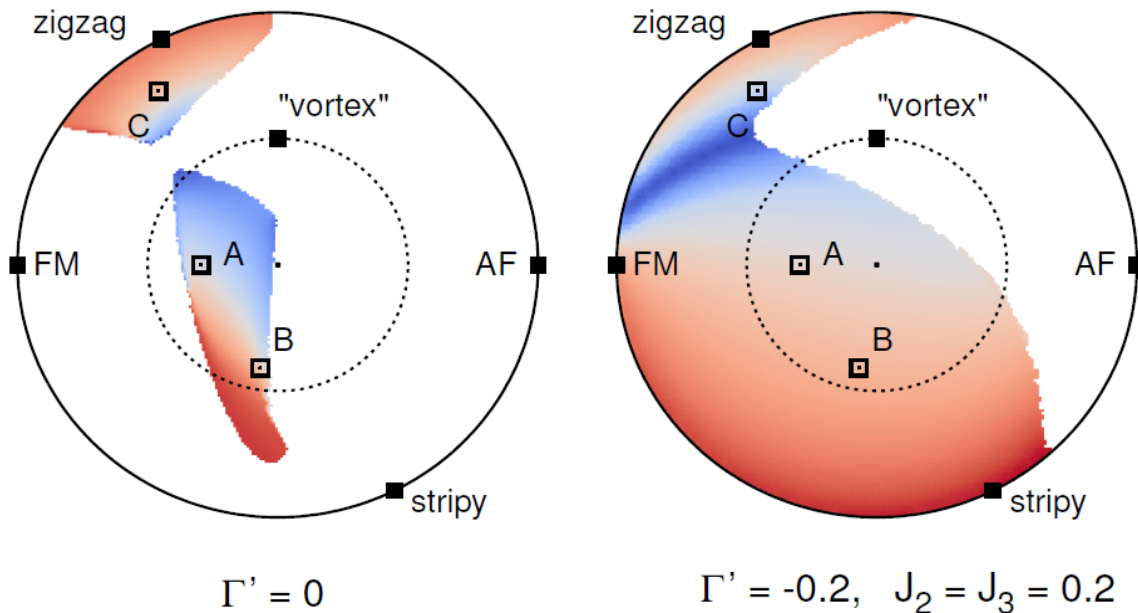
Frustrovaný magnetizmus voštinových iridátov



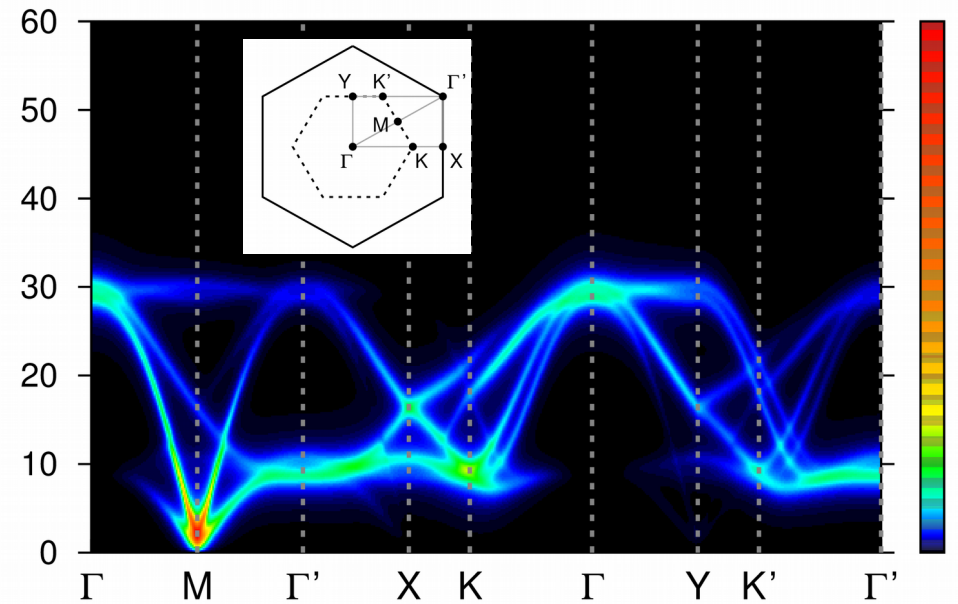
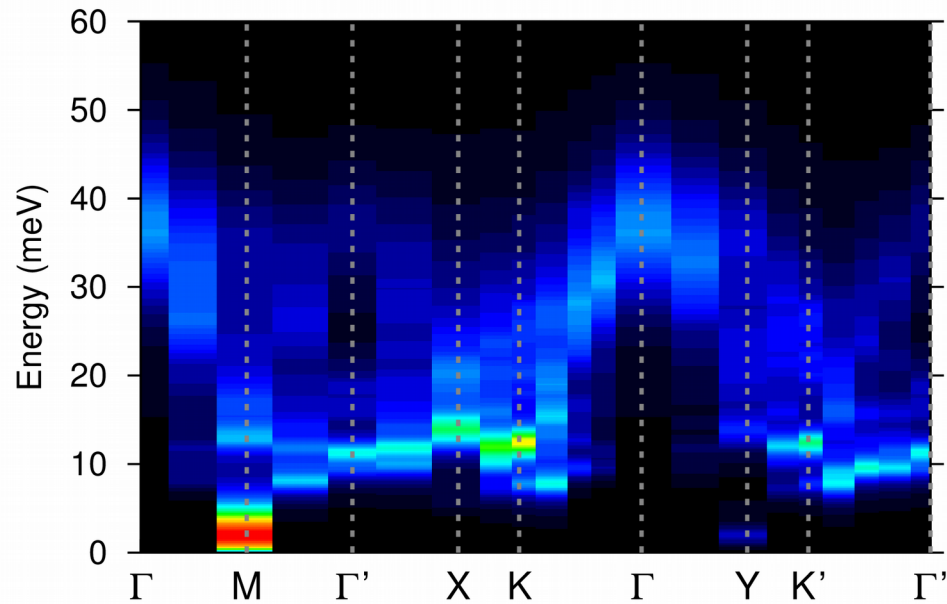
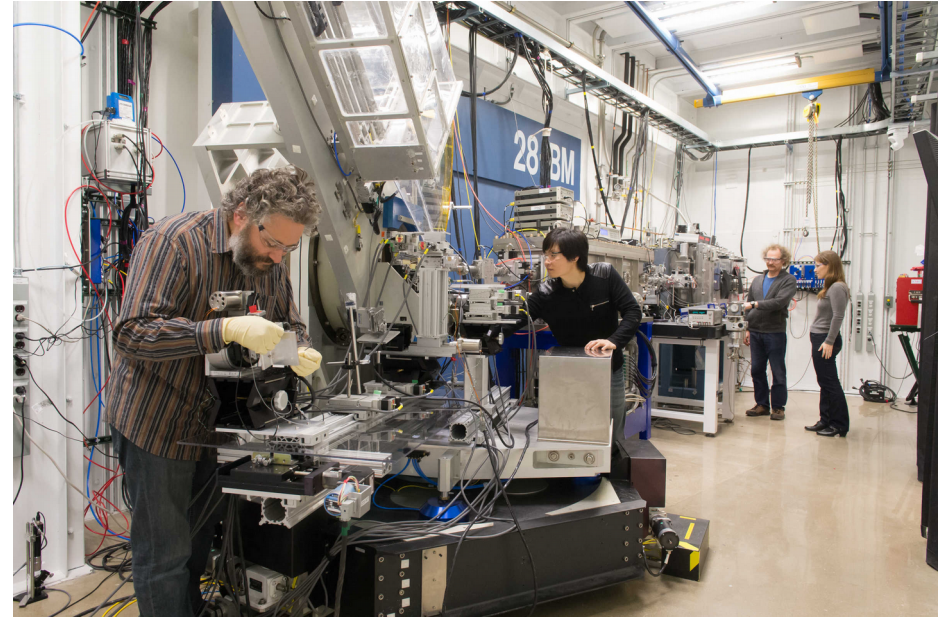
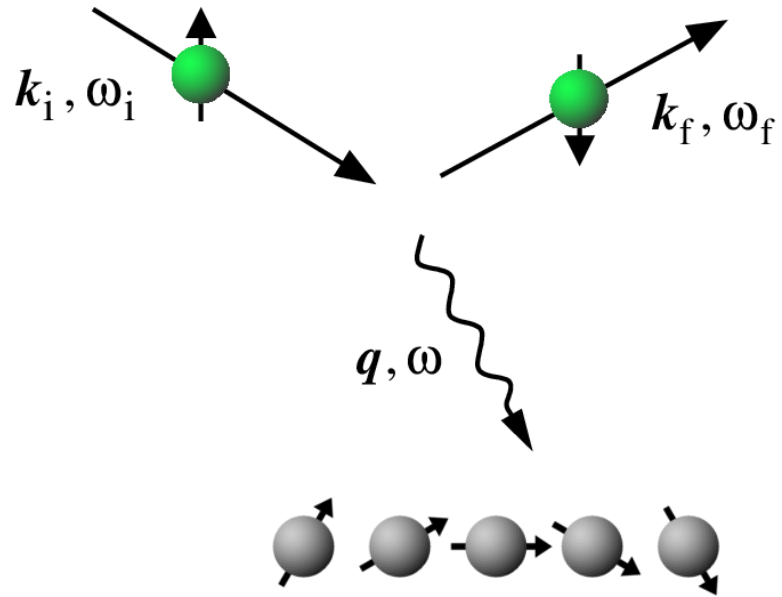
Súperenie magnetických interakcií



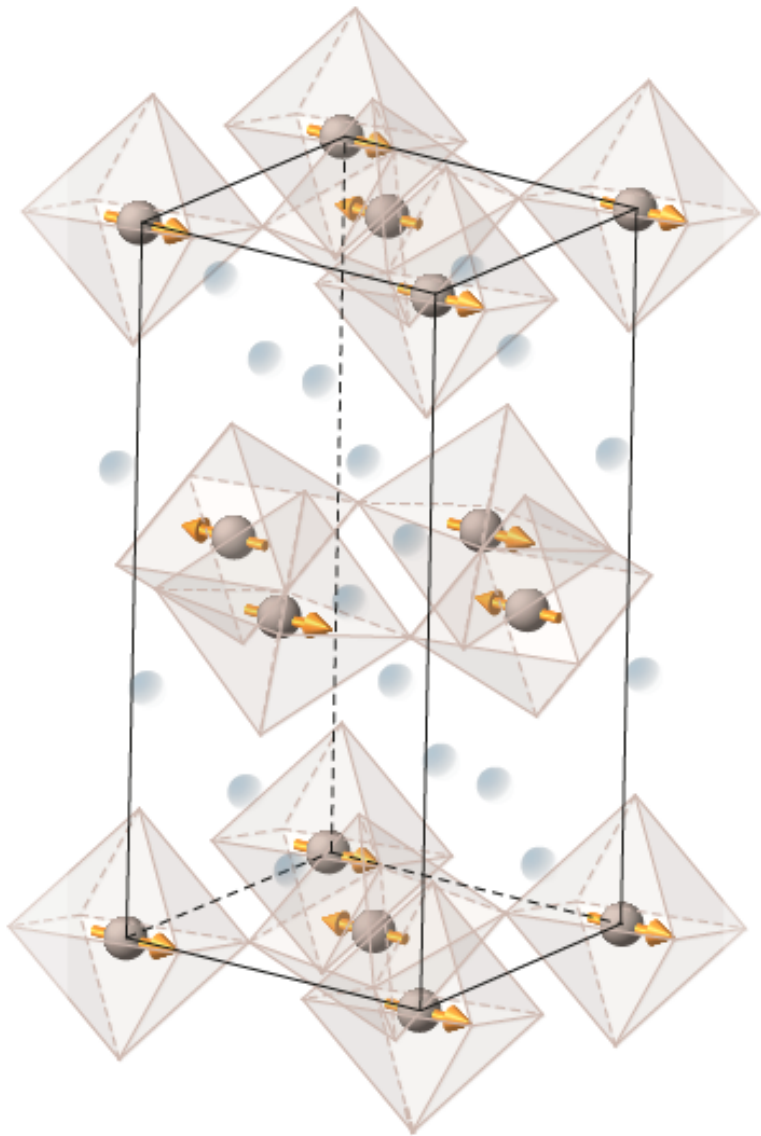
$$\mathcal{H}_{\langle ij \rangle \parallel c} = J \mathbf{S}_i \cdot \mathbf{S}_j + K S_i^z S_j^z + \Gamma (S_i^x S_j^y + S_i^y S_j^x) + \Gamma' (S_i^x S_j^z + S_i^z S_j^x + S_i^y S_j^z + S_i^z S_j^y)$$



Spinové excitácie



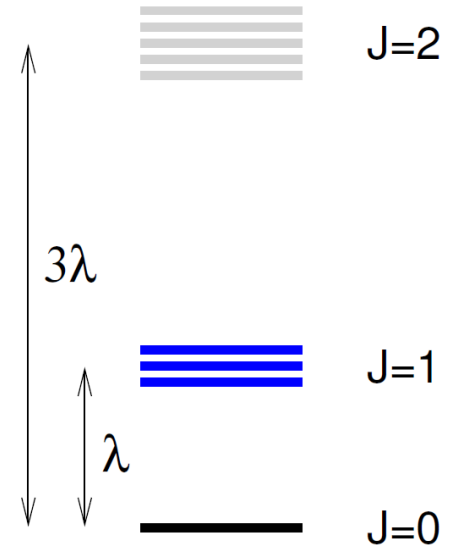
Higgsov mód v ruthenáte Ca_2RuO_4



$$t_{2g}^4$$

Energy level diagram for the t_{2g} orbitals. The ground state is labeled $S=1$ and $L=1$. The diagram shows three energy levels with arrows indicating the spin and orbital angular momentum of the electrons.

SOC \rightarrow



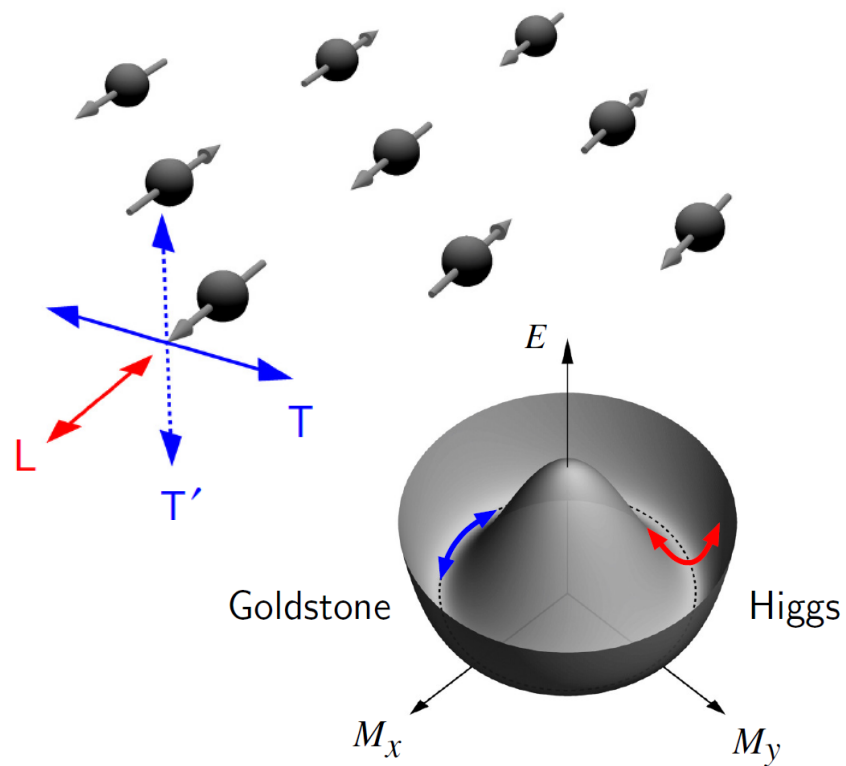
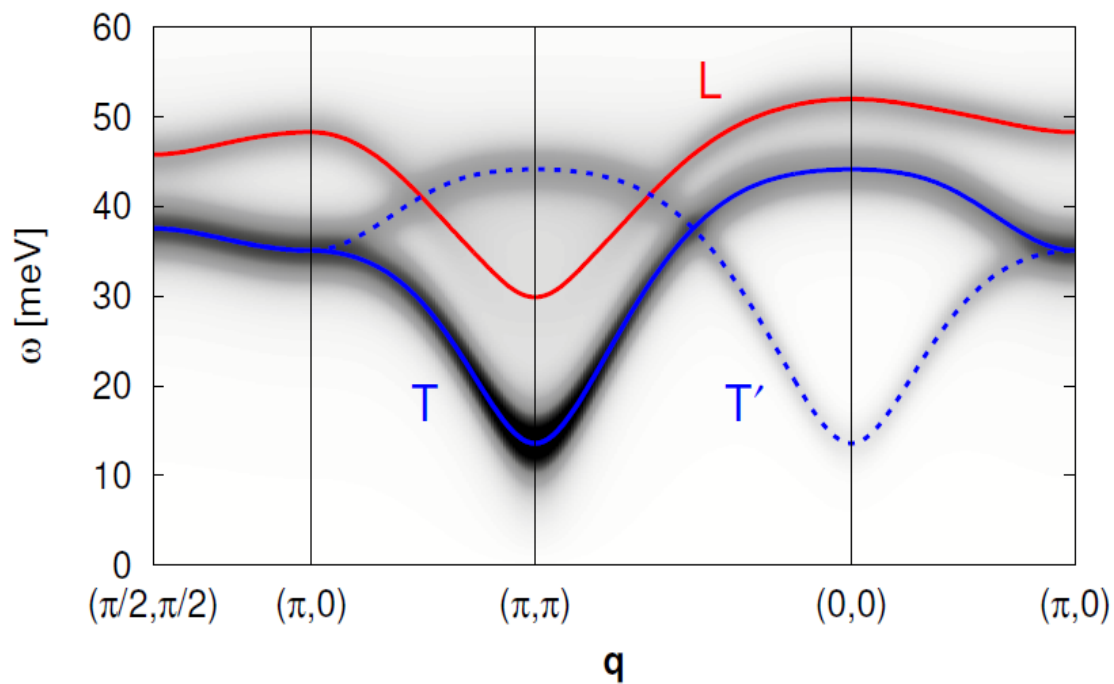
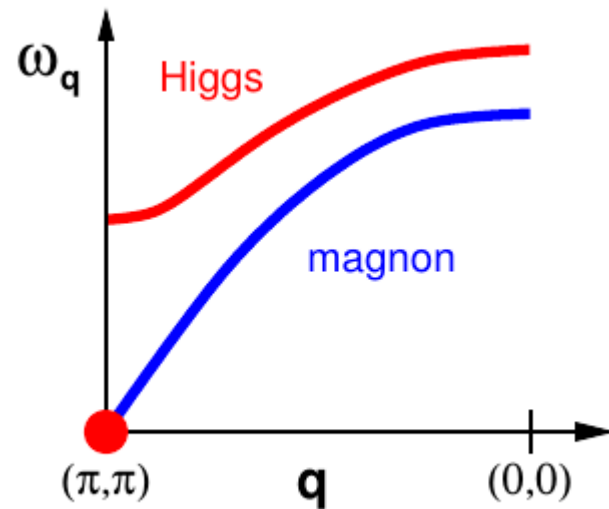
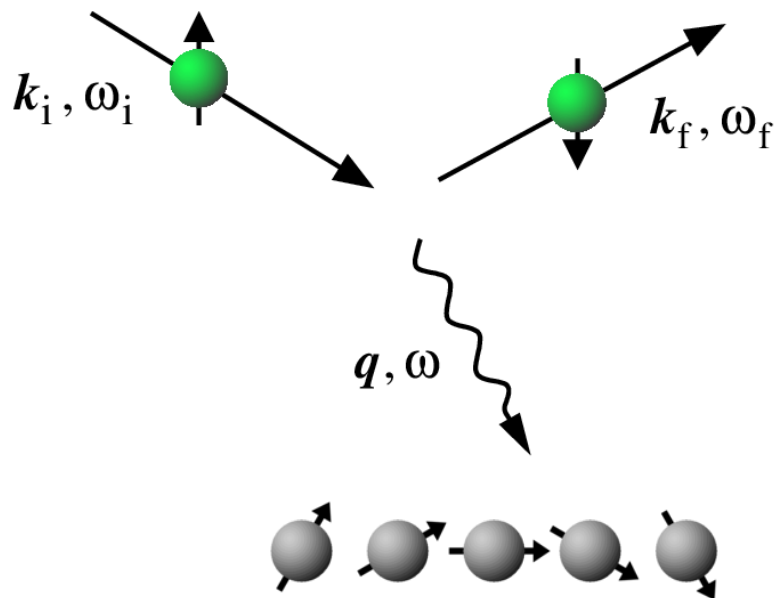
$$S = \frac{1}{\sqrt{3}} \left(\begin{array}{c} \uparrow \\ \uparrow \end{array} \times \begin{array}{c} \uparrow \\ \downarrow \end{array} + \begin{array}{c} \downarrow \\ \downarrow \end{array} \times \begin{array}{c} \downarrow \\ \uparrow \end{array} \right) - \frac{1}{\sqrt{6}} \left(\begin{array}{c} \uparrow \\ \downarrow \end{array} \times \begin{array}{c} \downarrow \\ \downarrow \end{array} + \begin{array}{c} \downarrow \\ \uparrow \end{array} \times \begin{array}{c} \uparrow \\ \uparrow \end{array} \right)$$

$$T_1 = \frac{1}{\sqrt{2}} \begin{array}{c} \uparrow \\ \uparrow \end{array} \times \begin{array}{c} \uparrow \\ \downarrow \end{array} + \frac{1}{2} \left(\begin{array}{c} \downarrow \\ \downarrow \end{array} \times \begin{array}{c} \uparrow \\ \uparrow \end{array} - \begin{array}{c} \downarrow \\ \uparrow \end{array} \times \begin{array}{c} \downarrow \\ \downarrow \end{array} \right)$$

$$T_0 = \frac{1}{\sqrt{2}} \left(\begin{array}{c} \uparrow \\ \uparrow \end{array} \times \begin{array}{c} \uparrow \\ \downarrow \end{array} - \begin{array}{c} \downarrow \\ \downarrow \end{array} \times \begin{array}{c} \downarrow \\ \uparrow \end{array} \right)$$

$$T_{-1} = -\frac{1}{\sqrt{2}} \begin{array}{c} \downarrow \\ \downarrow \end{array} \times \begin{array}{c} \downarrow \\ \downarrow \end{array} + \frac{1}{2} \left(\begin{array}{c} \uparrow \\ \uparrow \end{array} \times \begin{array}{c} \downarrow \\ \downarrow \end{array} - \begin{array}{c} \uparrow \\ \downarrow \end{array} \times \begin{array}{c} \downarrow \\ \uparrow \end{array} \right)$$

Kondenzát tripletov a jeho módy



Neutrónový rozptyl

