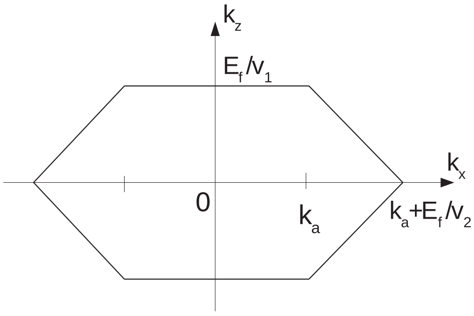

Fig. 1. Conduction band model $\varepsilon_{\boldsymbol{k}}$ for $k_y = 0$.

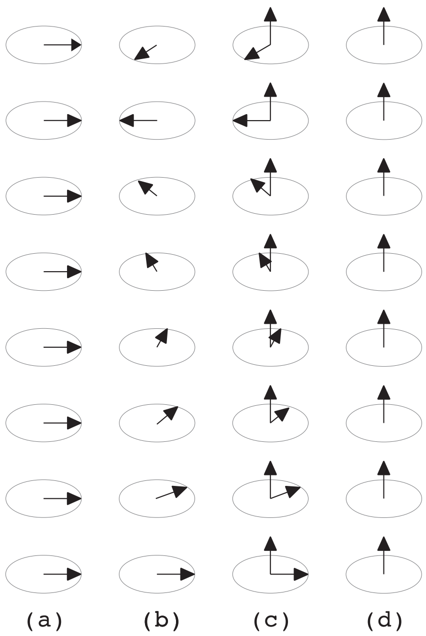

Fig. 2. Magnetic ordered structures of $\langle S_n \rangle$: (a) ferromagnet ($\boldsymbol{Q} = \boldsymbol{0}$, $\theta = \pi/2$); (b) helix ($\boldsymbol{Q} \neq \boldsymbol{0}, \theta = \pi/2$); (c) cone ($\boldsymbol{Q} \neq \boldsymbol{0}, 0 < \theta < \pi/2$); (d) ferromagnet ($\boldsymbol{Q} \neq \boldsymbol{0}, \theta = 0$).

with a cone angle θ and a helical wave vector $\boldsymbol{Q}$ along the k_z axis as shown in Fig. 2 [3],

$$\langle \boldsymbol{S}_n \rangle = \langle S \rangle \, (\sin\theta\cos\phi_n, \sin\theta\sin\phi_n, \cos\theta). \tag{5}$$

where $\phi_n = (\boldsymbol{Q} \cdot \boldsymbol{R}_n)$ is the turn angle. This cone structure becomes the helical structure for $\theta = \pi/2$ and the ferromagnetic structure for $\theta = 0$ or $\boldsymbol{Q} = \boldsymbol{0}$.

If there is no crystalline anisotropy, the cone axis can be in any direction. For an anisotropy of easy plane the cone axis is the c-direction while for an anisotropy of easy c-axis, the situation is more complicated [5,20].

For the first transformation the local axes (ξ_n, η_n, ζ_n) are introduced at each site $\boldsymbol{R}_n$, where ζ_n is defined to be along the direction of the local moment $\langle \boldsymbol{S}_n \rangle$, ξ_n along the direction perpendicular to both ζ_n and z axes, and η_n along the direction perpendicular to ζ_n and η_n axes as shown in Fig. 3. Those unit vectors $\boldsymbol{e}_{n\xi}$, $\boldsymbol{e}_{n\eta}$, $\boldsymbol{e}_{n\zeta}$ are given by

$$\left.\begin{aligned} \boldsymbol{e}_{n\xi} &= (\cos\theta\cos\phi_n, \cos\theta\sin\phi_n, -\sin\theta), \\ \boldsymbol{e}_{n\eta} &= (-\sin\phi_n, \cos\phi_n, 0), \\ \boldsymbol{e}_{n\zeta} &= (\sin\theta\cos\phi_n, \sin\theta\sin\phi_n, \cos\theta). \end{aligned}\right\} \tag{6}$$

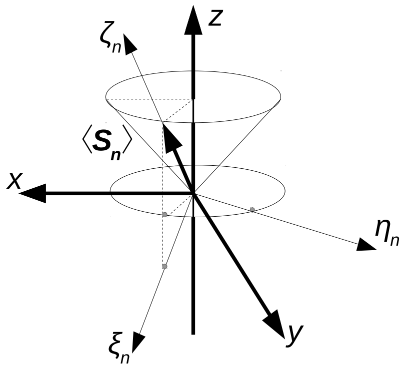

Fig. 3. Local coordinate axes (ξ_n, η_n, ζ_n).

Hence the f-spin operator $S_{n\xi}$, $S_{n\eta}$, $S_{n\zeta}$ are defined by

$$\boldsymbol{S}_n = S_{n\xi}\, \boldsymbol{e}_{n\xi} + S_{n\eta}\, \boldsymbol{e}_{n\eta} + S_{n\zeta}\, \boldsymbol{e}_{n\zeta}. \tag{7}$$

The unperturbed Hamiltonian H_0 is diagonalized by the transformation,

$$\left.\begin{aligned} A_{\boldsymbol{k}-} &= a_{\boldsymbol{k}\uparrow}\cos\theta_{\boldsymbol{k}} + a_{\boldsymbol{k}-\boldsymbol{Q}\downarrow}\sin\theta_{\boldsymbol{k}} \\ A_{\boldsymbol{k}+} &= -a_{\boldsymbol{k}\uparrow}\sin\theta_{\boldsymbol{k}} + a_{\boldsymbol{k}-\boldsymbol{Q}\downarrow}\cos\theta_{\boldsymbol{k}} \end{aligned}\right\} \tag{8}$$

with

$$\cos(2\theta_{\boldsymbol{k}}) = \frac{\varepsilon_{\boldsymbol{k}-\boldsymbol{Q}} - \varepsilon_{\boldsymbol{k}} + 2y}{\sqrt{(\varepsilon_{\boldsymbol{k}-\boldsymbol{Q}} - \varepsilon_{\boldsymbol{k}} + 2y)^2 + 4x^2}} \tag{9}$$

where $0 \le \theta_{\boldsymbol{k}} \le \frac{\pi}{2}$ and

$$x = I\langle S \rangle \sin\theta, \quad y = I\langle S \rangle \cos\theta\,. \tag{10}$$

After these two transformations, the Hamiltonian H_1 is rewritten as

$$\left.\begin{aligned} H &= H_0 + H_1 \\ H_0 &= \textstyle\sum_{\boldsymbol{k}\mu} E_{\boldsymbol{k}\mu} A^\dagger_{\boldsymbol{k}\mu} A_{\boldsymbol{k}\mu} \\ H_1 &= -IN^{-1}\textstyle\sum_{\boldsymbol{k}}\sum_{\boldsymbol{k}'}\sum_n \mathrm{e}^{\mathrm{i}(\boldsymbol{k}-\boldsymbol{k}')\cdot\boldsymbol{R}_n} \\ &\quad\times (A^\dagger_{\boldsymbol{k}-}\ A^\dagger_{\boldsymbol{k}+})(\sigma_-(\boldsymbol{k},\boldsymbol{k}')S_{n+} \\ &\qquad+\sigma_+(\boldsymbol{k},\boldsymbol{k}')S_{n-} + \sigma_\zeta(\boldsymbol{k},\boldsymbol{k}')S_{n0}) \\ &\quad\times \begin{pmatrix} A_{\boldsymbol{k}'-} \\ A_{\boldsymbol{k}'+} \end{pmatrix} \end{aligned}\right\} \tag{11}$$

where the new dispersion energy of the conduction electron $E_{\boldsymbol{k}\mu}$ is given by (see Fig. 10)

$$\begin{aligned} E_{\boldsymbol{k}\pm} = \frac{1}{2}\,[\,\varepsilon_{\boldsymbol{k}} + \varepsilon_{\boldsymbol{k}-\boldsymbol{Q}} \\ \pm\sqrt{(\varepsilon_{\boldsymbol{k}-\boldsymbol{Q}} - \varepsilon_{\boldsymbol{k}} + 2y)^2 + 4x^2}\,]. \end{aligned} \tag{12}$$

The f-spin operators $S_{n\pm}$ and S_{n0} are

$$S_{n\pm} = S_{n\xi} \pm \mathrm{i}S_{n\eta}, \quad S_{n0} = S_{n\zeta} - \langle S \rangle, \tag{13}$$

and the new spin matrices $\sigma_\pm(\boldsymbol{k},\boldsymbol{k}')$ and $\sigma_\zeta(\boldsymbol{k},\boldsymbol{k}')$ operating on the pseudo spin $\pm$ in $A_{\boldsymbol{k}\pm}$ are

$$\left.\begin{aligned} \sigma_-(\boldsymbol{k},\boldsymbol{k}') &= \tfrac{1}{2}[\sigma_3\sin(\theta_{\boldsymbol{k}} + \theta_{\boldsymbol{k}'} - \theta) \\ &\quad+ \sigma_1\cos(\theta_{\boldsymbol{k}} + \theta_{\boldsymbol{k}'} - \theta) \\ &\quad- \mathrm{i}\sigma_2\cos(\theta_{\boldsymbol{k}} - \theta_{\boldsymbol{k}'}) \\ &\quad+ 1\ \sin(\theta_{\boldsymbol{k}} - \theta_{\boldsymbol{k}'})], \\ \sigma_+(\boldsymbol{k},\boldsymbol{k}') &= \sigma_-(\boldsymbol{k}',\boldsymbol{k})^\dagger, \\ \sigma_\zeta(\boldsymbol{k},\boldsymbol{k}') &= \sigma_3\cos(\theta_{\boldsymbol{k}} + \theta_{\boldsymbol{k}'} - \theta) \\ &\quad- \sigma_1\sin(\theta_{\boldsymbol{k}} + \theta_{\boldsymbol{k}'} - \theta), \end{aligned}\right\} \tag{14}$$