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INFLUENCE OF THE MAGNETIC ORDER ON CONDUCTION ELECTRONS IN ANTIFERROMAGNETIC SEMICONDUCTORS

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Abstract. Within the framework of the exchange *s-f* model the electronic spectrum of a wide band antiferromagnetic semiconductor is studied. The method of irreducible Green functions is used. It provides a possibility to account both the electron-magnon inelastic scattering processes and the electron scattering over the fluctuations of the sublattice magnetization. The renormalization of the electronic spectrum has been determined in a wide temperature range. It is concluded that a "blue shift" should be observed with decreasing temperature. All the electronic states in antiferromagnetic semiconductors are notably with a finite life time even at $T=0$.

Резюме. В рамках обменной *s-f* модели исследован электронный спектр широкозонного антиферромагнитного полупроводника. Использовался метод неприводимых функций Грина, который дает возможность единым образом рассматривать электрон-магнонные неупругие процессы рассеяния и процессы рассеяния электронов на флуктуациях намагниченности подрешеток. В широком температурном интервале определяется перенормировка спектра электронов. Сделан вывод о возможном наблюдении „синего сдвига" в спектре поглощения при уменьшении температуры. Указано на конечное затухание электрочных состояний в антиферромагнитном полупроводнике даже при $T=0$.

1. Introduction

One of the most interesting problems in the physics of magnetic semiconductors is related to the study of the electron-magnon interaction processes. The electrons in these condensed systems could be conditionally divided into two groups: free carriers in the conduction band that form the semiconductor's electrical conductivity, and electrons that are localized at the atoms (*d*- or *f*-electrons) which define the atoms magnetic properties [1]. The magnetic semiconductors are also interesting because they are described by a model Hamiltonian, whose applicability has been reliably determined [1, 2].

The calculation of the re-normalized spectra of the magnetic and electronic subsystems and the corresponding densities of states is necessary to describe a number of properties of the magnetic semiconductors. Moreover, from the point of view of their magnetic order, they are ferromagnetic (EuO, EuS), metamagnetic (EuSe) and antiferromagnetic (EuTe). As a rule, the ferromagnetic semiconductors [1, 3] are the main object of theoretical studies. In a number of papers published recently [4—10] using the many-particle approaches, it was shown that the exchange interaction bet-

ween the subsystems of localized spins and the itinerant electrons yields a complicated temperature and concentrational dependence on the electronic quasiparticle spectrum.

Few papers [11—16] are only devoted to the theoretical study of antiferromagnetic semiconductors. In these compounds the itinerant electron motion occurs on the background of a complicated magnetic structure (a two-sublattice structure in the simplest case). As a rule the mean field approximation turns out to be insufficient [12] because missing the correlation effects between the electrons.

In the present work, the re-normalized quasiparticle spectrum of the wide-band antiferromagnetic semiconductor is calculated by the irreducible Green function method [17, 18], which has been successfully applied to the study of the elementary excitation spectra in ferromagnetic semiconductors [9, 10] and antiferromagnetic dielectrics [19]. The method uses the equations of motion for the two-time temperature Green functions [20] and the decoupling procedure being applied only for an approximate calculation of the mass operator. This provides a possibility to obtain a self-consistent systems of equations by neglecting the renormalization of the electron-magnon interaction. Thus, the irreducible Green function method can be used to calculate the quasiparticle spectra accounting for the correlation effects by unified self-consistent way

2. *s-f* model of an antiferromagnetic semiconductor

The exchange *s-f* model is the generally accepted model for magnetic semiconductors [1]. We shall consider EuTe as a typical antiferromagnetic semiconductor. The magnetic moments, formed by the 4*f* electrons of Eu^{2+}, are ordered in two interpenetrating sublattices *a* and *b*. Each lattice is ferromagnetic but the two sublattices have opposite magnetization and the total magnetic moment of the crystal is zero at all temperatures. Due to the strong 4*f*-electron localization, the system of magnetic moments is described by the Heisenberg Hamiltonian

$$H_f = \sum_{i \neq j}' \sum_{\alpha\beta}' J_{ij}^{\alpha\beta} \mathbf{S}_{i\alpha} \cdot \mathbf{S}_{j\beta} = \sum_{\mathbf{q},\alpha\beta}' J_q^{\alpha\beta} \mathbf{S}_{\mathbf{q}\alpha} \cdot \mathbf{S}_{-\mathbf{q}\beta}, \tag{1}$$

where $J_{ij}^{\alpha\beta}$ is the exchange integral between two spins at i site of sublattice α and j site of sublattice β. This integral is considered as parameter. Here the spin operators $\mathbf{S}_{i\alpha}(\mathbf{S}_{q\alpha})$ have the generally accepted meaning.

Itinerant electrons that form the second subsystem of the antiferromagnetic semiconductor are described by the Hamiltonian

$$H_s = \sum_{\mathbf{k}\sigma}' \sum_{\alpha\beta}' t_{\mathbf{k}}^{\alpha\beta} a_\alpha^+(\mathbf{k}\sigma)\, a_\beta(\mathbf{k}\sigma). \tag{2}$$

Here the operators $a_\alpha^+(\mathbf{k}\sigma)$ and $a_\alpha(\mathbf{k}\sigma)$ are those that create and annihilate an electron with wave vector $\mathbf{k}$ and spin σ in the sublattice numbered α and $t_{\mathbf{k}}^{\alpha\beta}$ are the electron energies ($\alpha=\beta$) and the overlap integrals ($\alpha\neq\beta$). As a rule, to simplify, these electrons are considered as itinerant *s*-electrons.

The two subsystems are coupled through a local spin-spin interaction

$$H_{s-f} = -\frac{I}{\sqrt{N}} \sum_{\mathbf{k}\mathbf{q}\sigma}' \sum_{\alpha}' [S_{-\mathbf{q}\alpha}^{-\sigma} a_\alpha^+(\mathbf{k}\sigma) a_\alpha(\mathbf{k}+\mathbf{q}-\sigma) + z_\sigma S_{\mathbf{q}\alpha}^z a_\alpha^+(\mathbf{k}\sigma) a_\alpha(\mathbf{k}+\mathbf{q}\sigma)], \tag{3}$$

where the exchange integral I has the typical value 0.1 eV for EuTe [1]. Thus the total Hamiltonian of the antiferromagnetic semiconductor is given by the sum

$$H = H_f + H_s + H_{s-f}. \tag{4}$$

Taking into account that $J^{\alpha\beta} \sim 10^{-3}$ eV, when studying the electron subsystem one can consider the reduced Hamiltonian

$$H \approx H_s + H_{s-f}. \tag{5}$$

In subsequent Sections the electronic spectrum of an antiferromagnetic semiconductor would be determined on the basis of the Hamiltonian (5).

3. Derivation of the Dyson equation

To calculate the electronic spectrum of a two-sublattice antiferromagnetic semiconductor, we shall consider the two-time temperature Green function (GF) in the following form:

$$G(t-t') = \ll A(t),\ B(t') \gg = -i\theta(t-t') < [A(t),\ B(t')]_+ >. \tag{6}$$

The structure of the Hamiltonian (2) shows that in this case it is suitable to choose a matrix GF

$$\hat{G}(\mathbf{k}\sigma,\ \omega) = \begin{pmatrix} \ll a_a(\mathbf{k}\sigma) \mid a_a^+(\mathbf{k}\sigma) \gg & \ll a_a(\mathbf{k}\sigma) \mid a_b^+(\mathbf{k}\sigma) \gg \\ \ll a_b(\mathbf{k}\sigma) \mid a_a^+(\mathbf{k}\sigma) \gg & \ll a_b(\mathbf{k}\sigma) \mid a_b^+(\mathbf{k}\sigma) \gg \end{pmatrix}, \tag{7}$$

where a and b refer to the different sublattices. The equation of motion for the Fourier transform of the elements of GF (7) are written as

$$\sum_{\gamma}{}' (\omega\delta_{\alpha\gamma} - t_{\mathbf{k}}^{\alpha\gamma}) \ll a_\gamma(\mathbf{k}\sigma) \mid a_\beta^+(\mathbf{k}\sigma) \gg = \delta_{\alpha\beta} - \ll A_{\mathbf{k}\sigma,\alpha} \mid a_\beta^+(\mathbf{k}\sigma) \gg. \tag{8}$$

The following notations have been introduced here

$$A_{\mathbf{k}\sigma,\alpha} = \frac{I}{\sqrt{N}} \sum_{\mathbf{q}} \ll S_{-\mathbf{q}\alpha}^{-\sigma}\, a_\alpha(\mathbf{k}+\mathbf{q}-\sigma) + z_\sigma S_{-\mathbf{q}\alpha}^z\, a_\alpha(\mathbf{k}+\mathbf{q}\sigma) \mid a_\beta^+(\mathbf{k}\sigma) \gg,$$

$$z_\sigma = \begin{cases} +1, & \sigma = \uparrow (+) \\ -1, & \sigma = \downarrow (-). \end{cases} \tag{9}$$

To separate the mean field contributions from the higher order re-normalizations, defined by the inelastic electron-magnon scattering, we introduce by analogy with ref. [9] the irreducible GF using the operators

$$(S_{q\alpha}^z)^{ir} = S_{q\alpha}^z - < S_{q\alpha}^z > \delta_{\mathbf{q}0}. \tag{10}$$

This choice is exactly determined by the condition

$$< [(S_{-\mathbf{q},\alpha}^z)^{ir}\, a_\alpha(\mathbf{k}+\mathbf{q}\sigma),\quad a_\beta^+(\mathbf{k}\sigma)]_+ > = 0. \tag{11}$$

The irreducible GF are so defined that they could not be reduced by decoupling to lower order functions. Moreover, the nonhomogeneous terms in the equations for the irreducible GF vanish.

Taking into account (10), eqn. (8) acquires the form:

$$\sum_{\gamma}{}' \{[\omega - \varepsilon_\alpha(\mathbf{k}\sigma)]\delta_{\alpha\gamma} - t_{\mathbf{k}}^{\alpha\gamma}(1-\delta_{\alpha\gamma})\} \ll a_\gamma(\mathbf{k}\sigma) \mid a_\beta^+(\mathbf{k}\sigma) \gg = \delta_{\alpha\beta} - \ll A_{\mathbf{k}\sigma,\alpha}^{ir} \mid a_\beta^+(\mathbf{k}\sigma) \gg, \tag{12}$$

where

$$\varepsilon_a(\mathbf{k}\sigma)=t_{\mathbf{k}}^{aa}-z_\sigma\frac{I}{\sqrt{N}}<S_{0a}^z>. \tag{13}$$

To calculate the GF in (12) we use the equation of motion that is obtained after differentiating with respect to t'. Thus for GF $\hat{G}(\mathbf{k}\sigma,\ \omega)$ the Dyson equation is obtained

$$\hat{G}(\mathbf{k}\sigma,\ \omega)=\hat{G}_0(\mathbf{k}\sigma,\ \omega)+\hat{G}_0(\mathbf{k}\sigma,\ \omega)\hat{M}(\mathbf{k}\sigma,\ \omega)\hat{G}(\mathbf{k}\sigma,\ \omega). \tag{14}$$

Here $\hat{G}_0(\mathbf{k}\sigma,\ \omega)=\hat{\Omega}^{-1}$ describes the behaviour of the electronic subsystem in the gene ralized Hartree-Fock approximation as

$$\hat{\Omega}(\mathbf{k}\sigma,\ \omega)=\begin{pmatrix}\omega-\varepsilon_a(\mathbf{k}\sigma) & -t_{\mathbf{k}}^{ab}\\ -t_{\mathbf{k}}^{ba} & \omega-\varepsilon_b(\mathbf{k}\sigma)\end{pmatrix}, \tag{15}$$

and the mass operator $\hat{M}(\mathbf{k}\sigma,\ \omega)$ is given as a connected part of the irreducible matrix GF of higher order

$$\hat{M}(\mathbf{k}\sigma,\ \omega)=\begin{pmatrix}\ll A_{\mathbf{k}\sigma,a}^{ir}\mid A_{\mathbf{k}\sigma,a}^{+,ir}\gg^{(c)} & \ll A_{\mathbf{k}\sigma,a}^{ir}\mid A_{\mathbf{k}\sigma,b}^{+,ir}\gg^{(c)}\\ \ll A_{\mathbf{k}\sigma,b}^{ir}\mid A_{\mathbf{k}\sigma,a}^{+,ir}\gg^{(c)} & \ll A_{\mathbf{k}\sigma,b}^{ir}\mid A_{\mathbf{k}\sigma,b}^{+,ir}\gg^{(c)}\end{pmatrix}, \tag{16}$$

in full analogy with the approach that is based on the diagram technique. Equation (14) shows that the determination of GF $\hat{G}(\mathbf{k}\sigma,\ \omega)$ is reduced to finding $\hat{G}_0(\mathbf{k}\sigma,\ \omega)$ and the approximate calculation of the mass operator (16).

4. Electronic spectrum in mean field

The GF elements in generalized Hartree-Fock approximation have the form:

$$G_0^{aa}(\mathbf{k}\sigma,\ \omega)=\frac{u_{\mathbf{k}\sigma}^2}{\omega-\varepsilon_+(\mathbf{k}\sigma)}+\frac{v_{\mathbf{k}\sigma}^2}{\omega-\varepsilon_-(\mathbf{k}\sigma)},$$

$$G_0^{ab}(\mathbf{k}\sigma,\ \omega)=\frac{u_{\mathbf{k}\sigma}v_{\mathbf{k}\sigma}}{\omega-\varepsilon_+(\mathbf{k}\sigma)}-\frac{u_{\mathbf{k}\sigma}v_{\mathbf{k}\sigma}}{\omega-\varepsilon_-(\mathbf{k}\sigma)}=G_0^{ba}(\mathbf{k}\sigma,\ \omega), \tag{17}$$

$$G_0^{bb}(\mathbf{k}\sigma,\ \omega)=\frac{v_{\mathbf{k}\sigma}^2}{\omega-\varepsilon_+(\mathbf{k}\sigma)}+\frac{u_{\mathbf{k}\sigma}^2}{\omega-\varepsilon_-(\mathbf{k}\sigma)},$$

where

$$u_{\mathbf{k}\sigma}^2=\frac{1}{2}\left[1-z_\sigma\frac{IS_z}{\tau_k}\right],\quad v_{\mathbf{k}\sigma}^2=\frac{1}{2}\left[1+z_0\frac{IS_z}{\tau_k}\right], \tag{18}$$

$$\tau_k=[(t_{\mathbf{k}}^{ab})^2+I^2S_z^2]^{1/2},\quad S_z=\frac{\langle S_{0a}^z\rangle}{\sqrt{N}}.$$

It is assumed here that each sublattice is simply cubic and $t_{\mathbf{k}}^{\alpha\alpha}=0$ ($\alpha=a$ or b). The energies $\varepsilon_\pm(\mathbf{k}\sigma)=\pm\tau_{\mathbf{k}}$ yield two quasiparticle electron energy bands in the mean field approximation. These bands form the so-called "Zener model" [12]. The Bloch zones

$\pm t_k^{ab}$ at $T<T_N$ when the sublattices are magnetically ordered remain degenerate along the spin direction. It is seen that the bottom of the lower quasiparticle band $\varepsilon_-(\mathbf{k}\sigma)$ would be shifted to lower energies with decreasing temperature and it would define in the optical spectra a "red shift". Unfortunately, there is a drastic contradiction between the theoretical results in the mean field approximation and the experiment which in most cases produces a week "blue shift" [12]. To eliminate the contradiction it is essential to account for the inelastic interaction between electrons and magnons and the electron scattering by the fluctuations of the sublattice's magnetic moment. These processes may be evaluated by the mass operator.

5. Re-normalization of the quasiparticle spectrum

To find the re-normalization of the spectra and the damping of the quasiparticles it is necessary to determine the self energy for each type of excitations. This may be done by reverting to creation and annihilation operators of the quasiparticles in terms of the $u-v$ Bogolyubov transformation given by (18). Then the GF for each kind of quasiparticle would have the form:

$$G_{\pm}(\mathbf{k}\sigma) = \frac{1}{\omega-\varepsilon_{\pm}(\mathbf{k}\sigma)-\Sigma^{\pm}(\mathbf{k}\sigma,\ \omega)}, \tag{19}$$

where the self-energy operator $\Sigma^{\pm}(\mathbf{k}\sigma,\ \omega)$ comprises all matrix element of the mass operator (16) and is given by the expression:

$$\Sigma^{\pm}(\mathbf{k}\sigma,\ \omega) = \begin{Bmatrix} u_{\mathbf{k}\sigma}^2 \\ v_{\mathbf{k}\sigma}^2 \end{Bmatrix} M^{aa} \pm u_{\mathbf{k}\sigma} v_{\mathbf{k}\sigma}(M^{ab}+M^{ba}) + \begin{Bmatrix} v_{\mathbf{k}\sigma}^2 \\ u_{\mathbf{k}\sigma}^2 \end{Bmatrix} M^{bb}. \tag{20}$$

An approximate expression for the mass operator elements (16) that is suitable for the consideration of the role played by accounting for the different scattering processes may be obtained in the following way. Using the spectral theorem [20] and the decoupling of the higher order correlation functions in a way described elsewhere [9, 19] and neglecting the correlation in the electron and magnetic propagation $M^{\alpha\beta}$ is given by the expression:

$$M^{\alpha\beta}(\mathbf{k}\sigma) = \frac{I^2}{N} \sum_{\mathbf{q}} \int_{-\infty}^{+\infty} d\omega_1 d\omega_2 \frac{1+\nu(\omega_1)-n(\omega_2)}{\omega-\omega_1-\omega_2}$$

$$\times [m_{\alpha\beta}^{\sigma,-\sigma}(\mathbf{q},\ \omega_1) g_{\alpha\beta}(\mathbf{k}+\mathbf{q}-\sigma,\ \omega_2) + m_{\alpha\beta}^{z,z}(\mathbf{q},\ \omega_1) g_{\alpha\beta}(\mathbf{k}+\mathbf{q}\sigma,\ \omega_2)]. \tag{21}$$

In (21) the following notations have been used

$$m_{\alpha\beta}^{i,j}(\mathbf{q},\ \omega) = -\frac{1}{\pi} \operatorname{Im} \ll S_{\mathbf{q}\alpha}^i \mid S_{-\mathbf{q}\beta}^j \gg,$$

$$g_{\alpha\beta}(\mathbf{k}\sigma,\ \omega) = -\frac{1}{\pi} \operatorname{Im} \ll a_\alpha(\mathbf{k}\sigma) \mid a_\beta^+(\mathbf{k}\sigma) \gg, \tag{22}$$

$$i,\ j = +,\ -,\ z;\quad \alpha,\ \beta = a,\ b.$$

The functions $\nu(\omega)$ and $n(\omega)$ are Bose and Fermi distributions, respectively. Equation (20), taking into account (21), represents an approximate self-consistent expression for the mass operator of the corresponding kind of quasiparticles.

Since the self-consistent calculation of the mass operator is not based on a definite initial approximation, we may use as a first iteration approximation for the electron spectral density $g_{\alpha\beta}$ the two-pole expression corresponding to the GF structure for a mean field

$$g_{\alpha\beta}(\mathbf{k}\sigma,\ \omega)=\left\{\begin{array}{c} u^2_{\mathbf{k}\sigma} \\ u_{\mathbf{k}\sigma}v_{\mathbf{k}\sigma} \\ v^2_{\mathbf{k}\sigma} \end{array}\right\}\delta(\omega-E_+(\mathbf{k}\sigma))+\left\{\begin{array}{c} v^2_{\mathbf{k}\sigma} \\ -u_{\mathbf{k}\sigma}v_{\mathbf{k}\sigma} \\ u^2_{\mathbf{k}\sigma} \end{array}\right\}\delta(\omega-E_-(\mathbf{k}\sigma)). \tag{23}$$

Similarly, for the localized spin spectral density $m^{\sigma,-\sigma}_{\alpha\beta}(\mathbf{q},\omega)$ according to [19], we have

$$\frac{m^{\sigma,-\sigma}_{\alpha\beta}(\mathbf{q},\ \omega)}{2z_\sigma S_z}=\left\{\begin{array}{c} U^2_g \\ U_qV_q \\ V^2_q \end{array}\right\}\delta(\omega-z_\sigma\omega_q)-\left\{\begin{array}{c} V^2_q \\ U_qV_q \\ U^2_q \end{array}\right\}\delta(\omega+z_\sigma\omega_q), \tag{24}$$

where U_q and V_q define the unitary Bose transformation and ω_q is the energy of the anti ferromagnetic magnon. It should be noted here that an itinerant electron concentration is supposed with a finite value.

At low temperatures, as shown in [19], the spin operators $S^z_{q\alpha}$ are expressed simply by $S^+_{q\alpha}$ and $S^-_{q\alpha}$. Then, taking into account (22) and (23) and by neglecting the inter-band transitions for the self-energy operator of the electrons from the low-energy band $E_-(\mathbf{k}\sigma)$, we obtain

$$\Sigma^-(\mathbf{k}\sigma,\ \omega)=\frac{I^2S_z}{2N}\Sigma_q(U_q+V_q)^2\left\{\frac{1+\nu(\omega_q)-n[E_-(\mathbf{k}-\mathbf{q})]}{\omega-\omega_q-E_-(\mathbf{k}-\mathbf{q})}+\frac{\nu(\omega_q)+n[E_-(\mathbf{k}+\mathbf{q})]}{\omega+\omega_q-E_-(\mathbf{k}+\mathbf{q})}\right\} \tag{25}$$

$$+2\frac{I^2S_z^2}{N}\Sigma_{qp}(U_qU_{q+p}-V_qV_{q+p})^2\frac{\nu(\omega_{q+p})[1+\nu(\omega_q)]+n[E_-(\mathbf{k}+\mathbf{p})][\nu(\omega_q)-\nu(\omega_{q+p})]}{\omega+\omega_{q+p}-\omega_q-E_-(\mathbf{k}+\mathbf{p})},$$

When deriving (25) it should be taken into account that for a wide band antiferromagnetic semiconductor the coefficients $u_{\mathbf{k}\sigma}\approx v_{\mathbf{k}\sigma}\approx 1/\sqrt{2}$ up to the terms in I^2. Expression (25) generalizes the results for finite electron correlation obtained in [11, 14] on the basis of a decoupling scheme of the equation of motion for the GF. It accounts for the electron-magnon scattering processes with the participation of one or two magnons. Its structure shows that in an antiferromagnetic semiconductor, the behaviour of the electrons (regardless of their spin) comprises the typical peculiarities of the electron states in a ferromagnetic semiconductor both with spin up ($\uparrow$) and spin down ($\downarrow$) [9].

The real part of the self-energy (25) determines the re-normalization of the electronic spectrum. At $T=0$ and empty conduction band the shift of the band bottom δE_- is given approximately by the expression:

$$\delta E_-=-\frac{I^2S}{WN}\sum_q{}'\frac{1}{\sqrt{1-\gamma_q^2}}, \tag{26}$$

where W is the band width and γ_q is the structure factor.

The mass-operator representation (16) provides a possibility to obtain an approximate expression for temperatures close to T_N. Using the static approximation for the correlation functions of the magnon subsystem (see [9]), the following expression is readily obtained:

$$M^{\alpha\beta}(\mathbf{k}\sigma) = \frac{I^2}{N}\sum_{\mathbf{q}}' \int_{-\infty}^{+\infty}\frac{d\omega'}{\omega-\omega'}\{<S^{-\sigma}_{-\mathbf{q}\beta}S^{\sigma}_{\mathbf{q}\alpha}>g_{\alpha\beta}(\mathbf{k}+\mathbf{q}-\sigma,\ \omega')$$
$$+<(S^z_{-\mathbf{q}\beta})^{\mathrm{ir}}(S^z_{\mathbf{q}\alpha})^{\mathrm{ir}}>g_{\alpha\beta}(\mathbf{k}+\mathbf{q}\sigma,\ \omega')\}. \tag{27}$$

Then with the help of the correlation functions from [13] and (23), neglecting the inter-band transitions in the case of wide-band semiconductor, we obtain

$$\Sigma^{-}(\mathbf{k}\sigma) = \frac{I^2}{2N}\sum_{\mathbf{q}}'\frac{\chi^{-,+}(\mathbf{q})+\chi^{z,z}(\mathbf{q})}{\omega-E_{-}(\mathbf{k}+\mathbf{q})}(1-\gamma_{\mathbf{q}}), \tag{28}$$

where

$$\chi^{-,+}(\mathbf{q}) = \frac{2S(S+1)/3}{1-\gamma^2_{\mathbf{q}}},$$
$$\chi^{z,z}(\mathbf{q}) = \frac{S(S+1)/3}{1-\gamma^2_{\mathbf{q}}+BS^2_z},\quad B=\frac{6(S^2+S+1/2)}{5S^2(S+1)^2}. \tag{29}$$

At $T=T_N$ the position of the band bottom is defined by the expression:

$$E_{-}(\mathbf{0}\sigma) = -\frac{W}{2}-\frac{I^2S(S+1)}{WN}\sum_{\mathbf{q}}'\frac{1}{1-\gamma^2_{\mathbf{q}}}. \tag{30}$$

Taking into account that at $T=0$

$$E_{-}(\mathbf{0}\sigma) = -\frac{W}{2}-\frac{I^2S^2}{W}-\frac{I^2S}{WN}\sum_{\mathbf{q}}'\frac{1}{\sqrt{1-\gamma^2_{\mathbf{q}}}} \tag{31}$$

by comparing (30) and (31) it follows that a "blue shift" would be observed with decreasing temperature. This sift for the model parameters $I=0.1$ eV, $S=7/2$, $W=1$ eV yields

$$\Delta E_{-} = E_{-}(T=T_N)-E_{-}(T=0)\approx -0.02 \text{ eV}.$$

This estimate is in a good agreement with experiment — 0.03 eV for EuTe [12].

The representation of the self-energy operator, defined by (25) and (27), shows that the quasiparticle states in the antiferromagnetic semiconductor possess a typical peculiarity — even at $T=0$ they turn out to be of finite life time. By this property they differ essentially from the electrons in ferromagnetic semiconductors, where finite damping at $T=0$ have only the down spin states. A detailed study of the damping of the electron states in the antiferromagnetic semiconductors requires a separate discussion.

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