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Correlation Functions in Spin Dynamics. Cross-Relaxation Form Functions of ^{8}Li and ^{6}Li Nuclei in LiF

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CORRELATION FUNCTIONS IN SPIN DYNAMICS. CROSS-RELAXATION FORM FUNCTIONS OF ^{8}Li AND ^{6}Li NUCLEI IN LiF: Preprint ITEP 80-94/

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Some general properties of one-spin and two-spin correlation functions in ordered and disordered spin systems are considered. This work also contains further development of the Anderson-Weiss-Kubo theory for taking into account dynamic correlations of local fields. As application we have calculated cross-relaxation functions of ^{8}Li and ^{6}Li nuclei in LiF single crystal.

Fig. - 3, ref. - 10

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I. *Different approaches for investigations of spin correlation functions*

At the beginning of the 60-th an understanding had been arisen that the language of correlation functions in statistical physics could serve as the base for consideration of all processes in the condensed state physics. For example, in conventional paramagnetic resonance, an observable (i.e. the magnetization) is usually proportional to the correlator of total spin

$$G^{\alpha}(t) = \langle I_{\alpha}(t) I_{\alpha} \rangle_0, \qquad I_{\alpha} = \sum_{i}^{N} I_i^{\alpha}, \tag{1}$$

$$\alpha = x, y, z, \qquad \langle \ldots \rangle_0 = \mathrm{Tr}(\ldots)/\mathrm{Tr}1,$$

where N is of order of total number of nuclei in a sample. In β-NMR and μSR the observable β-radiation asymmetry is proportional to the single-spin correlation function of the impuritive β-active nucleus (β-nucleus) or the muon:

$$G_0^{\alpha}(t) = \langle I_0^{\alpha}(t) I_0^{\alpha} \rangle_0. \tag{2}$$

This function is averaged over the position of radioactive probe in a crystal. Experiments on magnetic neutron scattering give an information about Fourier transform of another correlator

$$G_{ij}^{\alpha\beta} = \mathrm{Tr}(\rho I_i^{\alpha}(t) I_j^{\beta}). \tag{3}$$

Here ρ is the density matrix. All these correlation functions are single-particle because of two-particle type of the interaction of the probe radiation with the matter.

More complicated correlation functions are involved in observables indirectly via equations of motion. It makes difficult their experimental investigation. For example, polarization transfer over impuritive nuclei is described by the following equations [1]

$$p_{i0} = -\sum_{j} (\nu_{ji} p_{i0} - \nu_{ij} p_{j0}), \qquad p_{i0}(t=0) = \delta_{i0}. \tag{4}$$

Here $p_{i0}(t) = \mathrm{Tr}(I_i^z I_0^z(t))/\mathrm{Tr}(I_0^z)^2$ is the polarization of impuritive

nucleus "i", if the nucleus "0" was initially polarized; ν_{ij} is the polarization transfer probability between the nuclei, placed at i and j lattice sites, respectively (summation in Eq.4 is assumed over sites occupied by impurities only). It is important, that ν_{ij} is proportional to the cross-relaxation form-function

$$g^-_{ij}(\Delta_{ij}) = \int_{-\infty}^{+\infty} \frac{dt}{2\pi}\cdot\exp(i\Delta_{ij}t)\cdot g^-_{ij}(t), \qquad (5)$$

$$g^-_{ij}(t) = \langle I^+_i(t)I^-_j(t)I^+_jI^-_i\rangle_0/\langle I^+_iI^-_jI^+_jI^-_i\rangle_0 .$$

The Heizenberg evolution of the spin operators is determined, as usual, by the secular part of the dipole-dipole interaction. Let us consider, how much we can obtain from measurements of β-nuclei polarization $p_{00}(t)$ in β-NMR experiments [1] about the dependencies of $g^-_{ij}(\Delta_{ij})$ vs space separation r_{ij} between the nuclei and detuning $\Delta_{ij} = \Omega_i - \Omega_j$, where Ω_i is the Larmor frequency of the nucleus at "i" site. If all impuritive nuclei would occupied an ordered sublattice, the polarization of β-nuclei ensemble decreases exponentially, while $p_{00}(t) \geq 1/e$:

$$p_{00}(t) \approx \exp(-\sum_j \nu_{j0}t) . \qquad (6)$$

In this case the decay of $p_{00}(t)$ is determined only by one number $\sum_j \nu_{j0}$. Therefore, it is difficult to study the dependence g^-_{ij} vs r_{ij}. However, if impurities are randomly distributed over the lattice sites with the small concentration $c \ll 1$, the polarization of β-active nuclear probes, averaged over their positions in the crystal, is

$$\langle p_{00}(t)\rangle_c = \exp(-M_0(t) - M_1(t)), \qquad (7)$$

$$M_0(t) = c\cdot\sum_r \left[\frac{1-\exp[-(\xi_r+1)\nu_{r0}t]}{\xi_r+1} \right], \qquad \xi_r = \frac{I_0(I_0+1)}{I_r(I_r+1)} .$$

One turns out that $M_1(t)/M_0(t) < 0.01 \div 0.1$. when $M_0(t) \leq 1$ and $g^-_{ij}(\Delta) \approx g^-_{ij}(0)$ [1,2]. In reality the ratio $M_1(t)/M_0(t)$ depends on external magnetic field (see for details [2]). Eq.7 is much more complicated than Eq.5 and leads to the more informative comparison with experimental data.

In NMR investigations the depolarization of impuritive nucleus under the influence of alternating field with the amplitude ω_1 proceeds as a rule, exponentially

$$p_0(t) = \langle I_0^z(t) I_0^z \rangle_0 / \langle I_0^z I_0^z \rangle_0 = \exp(-Wt), \tag{8}$$

$$W = \pi\omega_1^2 g_0(\omega), \quad g_0(\omega) = \int_{-\infty}^{+\infty} \frac{dt}{2\pi} \cdot \exp(i\omega t) \cdot \langle I_0^+(t) I_0^- \rangle_0 / \langle I_0^+ I_0^- \rangle_0 .$$

Comparison between Eqs.7 and 8 allows to elucidate a profound internal analogy and difference among these methods: in both cases one obtains an information concerning transverse spin component correlator basing on an observation of longitudinal relaxation. The difference is that in Eq.8 stands one-spin correlator, while in Eq.7 - the two-spin function.

The basic approximation for two-spin correlation functions is $g_{ij}^-(t) \approx g_i(t) \cdot g_j(t)$, where $g_i(t) = \langle I_i^+(t) I_i^- \rangle_0 / \langle I_i^+ I_i^- \rangle_0$, which is accurate for $r_{ij} \to \infty$, when spins I_i and I_j precess independently. Deviations from this approximation are due to the correlations in their motion, caused by local magnetic fields of environment acting on impuritive spins. Investigation of the validity of this approximation is really possible in the disordered nuclear spin system made up from β-nucleus ^{8}Li and stable nuclei ^{6}Li, for instance, in LiF single crystal.

The simulation of the local field evolution by the normal random process was proposed by Anderson and Weiss for a qualitative explanation of the effect of narrowing by motion. In their model free-induction decay $g(t) = \langle \exp[i\int_0^t d\tau \cdot \hat{\omega}_0(\tau)] \rangle_0$ is expressed as $g(t) = \exp[-\int_0^t d\tau \cdot (t-\tau) \cdot \Lambda(\tau)]$, where $\Lambda(\tau) = \langle \hat{\omega}_0(\tau) \hat{\omega}_0(0) \rangle_0$, $\Lambda(0) = \langle \hat{\omega}_0^2 \rangle_0 = M_2$. Here $\hat{\omega}_0(\tau)$ is the operator of the local field on a nucleus, placed at r. If a characteristic time $\tau_c \sim \int_0^\infty dt \cdot \Lambda(\tau)$ of local field fluctuations is changed from $\tau_{c\infty} \gg 1/\sqrt{M_2}$ (static local fields) to $\tau_{c0} \ll 1/\sqrt{M_2}$ (rapid spin motion), $g(t)$ is varied from gaussian function $g_G(t) = \exp(-M_2 t^2/2)$ to the exponential function $g_L(t) = \exp(-\Gamma t)$, $\Gamma = M_2 \tau_c$, which decreases more slow at large t. Two simplest functions are usually used for qualitative description of intermediate cases: $\Lambda(\tau) = M_2 \exp(-|\tau|/\tau_c)$ corresponds to the translational hopping of the impuritive nuclei, and $\Lambda(\tau) = M_2 \exp(-\tau^2/2\tau_c^2)$ simulates more smooth processes, like local field fluctuations due to flip-flop processes of the host spins. For the sake of explicit calculation of the integrals involved, one uses $\Lambda(\tau) = \mathrm{ch}^{-2}(\tau/\tau_c)$.

Recently, it was shown [3] that the approximation of local field $\hat{\omega}_i(t)$ on an impuritive spin by a normal random process (Anderson-Weiss-Kubo (AWK) model [4,5]) with the natural properties of the correlator $\langle\hat{\omega}_0(t)\hat{\omega}_0\rangle_0$ leads to a very good agreement with the measured NMR form function $g_0(\omega) = \int_{-\infty}^{+\infty} \frac{dt}{2\pi}\cdot e^{i\omega t}\cdot g_0(t)$ up to $g_0(\omega) > 10^{-5}\cdot g_0(0)$. This fact seems rather puzzling, because the modern theory [6], aimed on the description of such phenomena, has only one small parameter - inverse coordination number 1/z, and does not pretend on such a high precision. To avoid uncertainty, we would like to note that the most surprising is the obtained gaussian-type time structure of local field fluctuations, while their instant distribution is gaussian within two orders of its variation from the top.

Investigation of the functions $g^-_{ij}(\omega)$ allow to verify the efficiency of the AWK model within the same ideas for the description of local field fluctuations in a new and much more complicated process then in [3].

Note, that β-NMR gives also a possibility to study the other similar correlation functions

$$g^+_{ij}(t) = \langle I^+_i(t)I^+_j(t)I^-_jI^-_i\rangle_0/\langle I^+_iI^+_jI^-_jI^-_i\rangle_0 \qquad (9)$$

by means of investigation of the form function of the resonance at $\omega = \omega_I + \omega_S$, where ω_I and ω_S are Larmor frequencies of ^{8}Li and ^{6}Li, respectively.

2. Cross-relaxation form functions

In this paper we present the detailed formulation of the general relationships, describing the correlation of local fields on impuritive nuclei, and preliminary comparison with available experimental data.

Cross-relaxation form functions (FFCR) could be represented as follows [2]

$$g^-_{0r}(\Omega_0-\Omega_r) = \int_{-\infty}^{+\infty} \frac{dt}{2\pi}\cdot\left[\tilde{g}^-_{0r}(t)\cdot\cos[(\Omega_0-\Omega_r)t] \cdot \phi_{0r}(t)\cdot\cos(2\alpha_{0r}t)\right], \qquad (10)$$

where Ω_r is the Larmor frequency of the impuritive spin, placed in r, α_{0r} is the coefficient of dipole-dipole interaction between

impuritive nuclei (see Eq.14),

$$\phi_{or}(t) = \mathrm{Tr}\left[I_o^+ I_r^- \cos(2a_{or}(I_o^z - I_r^z)t) I_o^- I_r^+\right] / \mathrm{Tr}(I_o^+ I_r^- I_r^+ I_o^-) =$$

$$= \frac{g}{4} \sum_{m_o=I_o}^{I_o} \sum_{m_r=I_r}^{I_r} \frac{I_o(I_o+1)-m_o(m_o+1)}{I_o(I_o+1)(2I_o+1)} \frac{I_r(I_r+1)-m_r(m_r+1)}{I_r(I_r+1)(2I_r+1)} \cos(2a_{or}(m_o-m_r)t)$$

and

$$\tilde{g}_{or}^-(t) = \langle \eta_o(t)\eta_r^+(t)\rangle_0, \quad \eta_r = \frac{1}{2}(T_+ + T_-) \exp\left[-i\int_0^t \hat{\omega}_r(\tau)d\tau\right]. \quad (11)$$

In Eq.11 T_+ and T_- order the following operators, according to their growing up and growing down in time, respectively. $\hat{\omega}_r(\tau)$ is the local field operator (its time evolution is determined by internal interactions of the host spins with each other). The relationship for $g_{or}^-(\Delta)$, used in [2], was obtained from Eq.10 neglecting a_{or}^2 in comparison with $\langle\omega_r^2\rangle_0$. Within the AWK model local fields are approximated by a normal random process and, thus, for $\tilde{g}_{or}^-(t)$ we obtain

$$\tilde{g}_{or}^-(t) = \exp\left[-\int_0^t d\tau(t-\tau)[A_{oo}(\tau)-2A_{or}(\tau)+A_{rr}(\tau)]\right] \approx$$

$$\approx \exp\left[-2\int_0^t d\tau(t-\tau)[A_{oo}(\tau)-A_{or}(\tau)]\right] \quad (12)$$

The last approximate equality holds if the difference in g-factors of impuritive nuclei is small (g-factors of ^{8}Li and ^{6}Li are 0,8267 and 0,8220, respectively). Here $A_{or}(t) = \langle\hat{\omega}_r(t)\cdot\hat{\omega}_o(0)\rangle_0$ is the correlator of the local fields created by the z-components of the host spins at a given pair of impuritive nuclei. Here and below o (i.e. r≡0) and r indicate lattice sites of ^{8}Li and ^{6}Li, respectively, and therefore they always belong to Li-sublattice. The spin I_o of ^{8}Li is 2 and ^{6}Li spin I_r= 1. Subscripts x,y and z will enumerate positions of ^{19}F or ^{7}Li nuclei only. In the following calculation of $A_{or}(\tau)$, the effect of impuritive spins on the host spins is ignored.

The operator of the local field at the position r of the impuritive nucleus can be written in frequency units as follows:

$$\hat{\omega}_r = \sum_{A=F,L} \hat{\omega}_r^{(A)}, \qquad \hat{\omega}_r^{(A)} = \sum_{x\in A} d_{rx}^{IA}\cdot A_x^z,$$

$$d^{IA}_{rx} = \omega_{IA}\cdot\tilde{d}^{IA}_{rx}, \qquad \omega_{IA} = \frac{g_I g_A \beta_n^2}{\hbar d^3}, \qquad \tilde{d}^{IA}_{rx} = \frac{1-3\cos^2\theta_{r-x}}{|(r-x)/d|^3} \tag{13}$$

The coordinate summation is carried out over all sites in fluorine or lithium sublattice. "A" enumerates F and Li sublattices and at the same time takes on the values F=1/2 or L=3/2, which are the spins of ^{19}F and ^{7}Li (operators of their z-components are F^z_x and L^z_x). d^{IA}_{rx} is the usual coefficient of dipole-dipole interaction of the spin I and A (if x=r, we set $\tilde{d}^{IA}_{rx}=0$). Dipole coefficient a_{or} in Eq.10 is determined by the similar relationship

$$a_{or} = \frac{g_I^2\beta_n^2}{2\hbar d^3}\cdot\tilde{d}_{or} = \frac{\omega_{II}}{2}\,\tilde{d}^{II}_{or}\,, \tag{14}$$

Using the values of the g-factors of ^{8}Li (^{6}Li), ^{19}F and ^{7}Li ($g_I \approx 0.824$, $g_F=5.257$ and $g_L=2.171$, respectively) and minimal distance between Li and F in LiF (d=2.01Å), we obtain ω_{IF}= 2.05 kHz, ω_{IL}= 0.85 kHz, ω_{II}= 0.322 kHz, ω_{FF}= 13.1 kHz, ω_{LL}= 2.23 kHz. Substituting Eq.13 into the expression for $\Lambda_{or}(t)$, we obtain

$$\Lambda_{or}(t) = \sum_{A=F,L}\Lambda^{(A)}_{or}(t),$$

$$\Lambda^{(A)}_{or}(t) = \langle\hat{\omega}^{(A)}_r(t)\cdot\hat{\omega}^{(A)}_o(0)\rangle_0 =$$

$$= \frac{A(A+1)}{3}\sum_{x\in A}\sum_{y\in A} d^{IA}_{ox}\, G^{AA}_{xy}(t)\, d^{AI}_{yr}. \tag{15}$$

Here we introduced the spin-diffusion propagator $G^{AA}_{xy}(t) = \langle A^z_x(t)A^z_y\rangle_0 / \langle(A^z_x)^2\rangle_0$, which satisfies the following equations [2,3]:

$$\partial G^{AA}_{xy}/\partial t_{eff} = -\sum_z \mathcal{A}^{AA}_{xz}\cdot G^{AA}_{zy}, \qquad G^{AA}_{xy}(t=0) = \delta_{xy},$$

$$\mathcal{A}^{AA}_{xy} = -\nu^{AA}_{xy} + \delta_{xy}\sum_z \nu^{AA}_{zx}\,, \qquad x,y,z \in \text{A-sublattice}, \tag{16}$$

where ν^{AA}_{xy} is the polarization transfer probability between two A spins

$$\nu^{AA}_{xy} = \frac{\pi A(A+1)}{6}\cdot(\omega^{AA}\tilde{d}^{AA}_{xy})^2\cdot T_{2A} = \frac{(\tilde{d}^{AA}_{xy})^2}{\tau_{cA}\sigma^{FF}}\,,$$

$$\sigma^{FF}=\sum_z(\tilde{d}^{AA}_{xz})^2,\qquad \sigma^{FF}\equiv\sigma^{LL},\qquad \omega^{AA}=\frac{(g_A\beta_n)^2}{hd^3},\qquad \frac{1}{\tau_{cA}}=\sum_z\nu^{AA}_{xz}.$$

Here τ_{cA} is the correlation time or the time of flip-flop process between A spins and $T_{2A}=\int_0^\infty g_{cA}(\tau)d\tau$ is their phase relaxation time. In Eq.13 $t^{(A)}_{eff}=\int_0^t(t-\tau)g_{cA}(\tau)\frac{d\tau}{T_{2A}}$ and stands for the smoothing of the spin-diffusion propagator at small $t\le T_{2A}$. It was shown in [3] that the choice of $g_{cA}(\tau)$ as $\exp(-M_{2A}\tau^2)$, $ch^{-2}\sqrt{M_{2A}}\tau$ or $(1+\frac{2}{3}\cdot M_{2A}\tau^2)^{-3/2}$, where M_{2A} is one-spin second moment of the host nuclei [1], has very small influence on NMR form function. For gaussian $g_{cA}(\tau)$ $T_{2F}=(2\pi M_{2F}(Hz^2))^{-1/2}=7.1\mu s$, $T_{2L}=16\mu s$, $\tau_{cF}=\left[\frac{\sqrt{\pi}}{12}F(F+1)\omega^2_{FF}\sigma^{FF}/\sqrt{M_{2F}(Hz^2)}\right]^{-1}=175\mu s$ and $\tau_{cL}=530\mu s$ for $[100]//\mathcal{H}_0$ orientation of the LiF crystal in external magnetic field $\mathcal{H}_0$.

Eqs.15-16 allow to obtain the final representation for $\Lambda^{(A)}_{or}(t)$, which was used in numerical calculations:

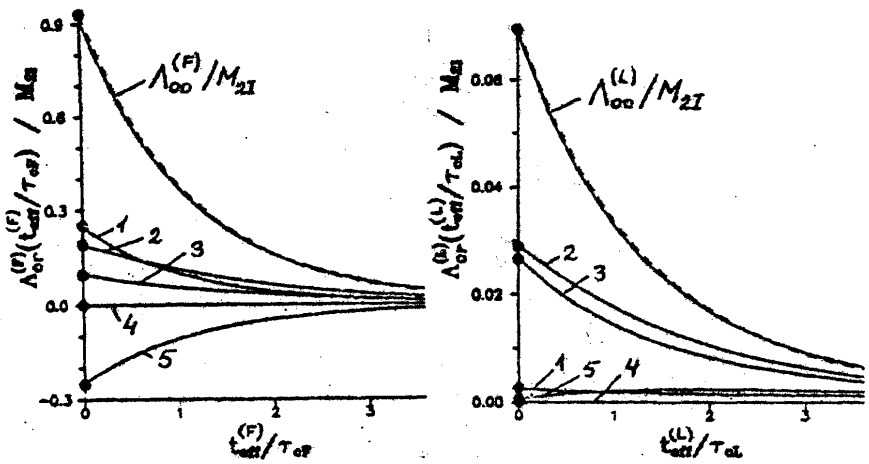
$$\Lambda^{(A)}_{or}(t)=\frac{A(A+1)}{3}\int_{B_1}\frac{\Omega\cdot d^3k}{(2\pi)^3}\,[d^{IA}(k)]^2\cdot\exp[ikr-\mathcal{d}^{AA}(k)t^{(A)}_{eff}],$$

$$\mathcal{d}^{AA}(k)=\sum_{x\in A}e^{-ikx}\mathcal{d}^{AA}_{yx}\ ,\qquad d^{IA}(k)=\sum_{x\in A}e^{-ikx}d^{IA}_{yx}\ . \tag{17}$$

Here B_1 is the Brilluen zone, $\Omega=2d^3$ stands for the volume of elementary cell of LiF crystal. The results of our calculations of $\Lambda^{(F)}_{or}(t)$ and $\Lambda^{(L)}_{or}(t)$ for different mutual arrangements of ^{8}Li and ^{6}Li spins are shown in Figs.1,2. We considered the cases when ^{6}Li is located on the first coordination sphere (two non-equivalent positions), on the second coordination sphere (again two non-equivalent positions) and when ^{8}Li and ^{6}Li are separated by a very large distance (in this case, obviously, no correlations in environmental local fields exist, and $\Lambda^{(A)}_{0,r\to\infty}(t)$ equals zero).

Obtained functions $\Lambda^{(A)}_{or}(t)$ were substituted into Eq.10 and, afterwards, the corresponding cross-relaxation form functions $g^-_{or}(\omega)$ were calculated. Results are shown on Fig.3 for the same mutual arrangements of ^{8}Li and ^{6}Li spins. For infinite separation $g^-_{0,r\to\infty}(\omega)$ is a convolution of two NMR form-functions, which we have

calculated in [3]. The points on this figure display the results of the fit of three runs of β-NMR experiments, where depolarization of ^{8}Li due to polarization transfer over ^{8}Li-^{6}Li spin system was measured [8]. In that fit the dependence of $g^-_{0r}(\omega)$ on r was ignored and the value of this form function was considered as a fitting parameter. We think that the discrepancy between these data and theoretical curves on the Fig.3 indicates first of all on an inadequate estimation of the accuracy of the measurement of ^{6}Li concentration in [3] (this concentration squared is a multiplier before the FFCR).



Figs.1,2. Correlators of local fields, induced by all surrounding ^{19}F (^{7}Li) spins on the nuclear pair ^{8}Li-^{6}Li, as a function of time. $\vec{H}_0$//[100]. Line 1 corresponds to the interpair separation $\vec{r}$ = d·(0,0,2); line 2 - $\vec{r}$ = d·(1,1,0); line 3 - $\vec{r}$ = d·(2,0,0); line 4 - r → ∞; line 5 - $\vec{r}$ = d·(1,0,1). Dashed lines present our results of analytical calculations of $\Lambda^{(F)}_{00}(t)$ and $\Lambda^{(L)}_{00}(t)$ taken from [3]. The points display the values of the correlation second moments or values of $\Lambda^{(A)}_{0r}(t=0) = \langle\hat{\omega}^{(A)}_r(0)\cdot\hat{\omega}^{(A)}_0(0)\rangle_0$ known from independent calculations [7]. An agreement between these values and our calculations of $\Lambda^{(A)}_{0r}(t)$ according Eq.16, gives the measure of accuracy of our numerical procedure.

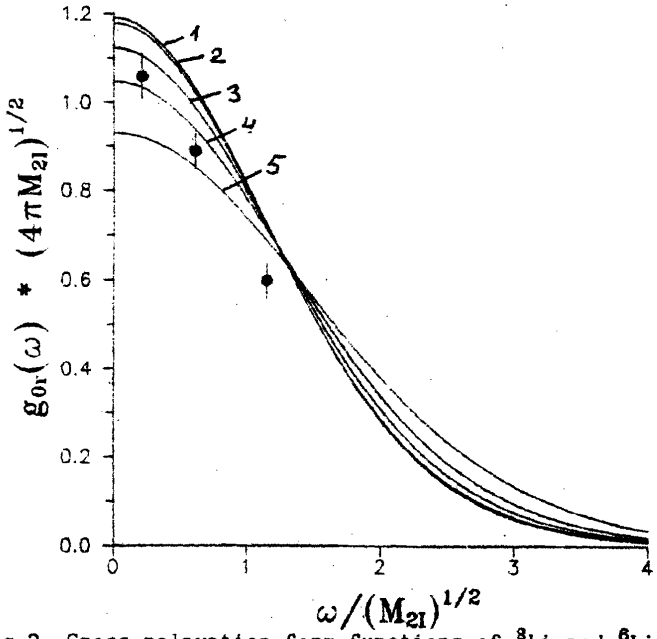


Fig.3. Cross-relaxation form functions of ^{8}Li and ^{6}Li spins in LiF. $\vec{H}_0$//[100], the second moment of the NMR form-function is $M_{2I} = \langle\hat{\omega}_0^2\rangle_0/(2\pi)^2 = 14.1\text{kHz}^2$. Line 1 corresponds to interpair separation $\vec{r} = d\cdot(0,0,2)$; line 2 - $\vec{r} = d\cdot(1,1,0)$; line 3 - $\vec{r} = d\cdot(2,0,0)$; line 4 - $r \to \infty$; line 5 - $\vec{r} = d\cdot(1,0,1)$.

3. Conclusion

Three exactly solvable models in the many-body theory played an outstanding role in the development of general ideas of the physical kinetics.

First of all it is the model of interaction of a two-level system with a field of radiation, described by the Hamiltonian

$$H = \omega_S S_z + \sum \omega_k a_k^+ a_k + \sum(g_k a_k^+ S^- + \text{h.c.}).$$

Here ω_S is the transition frequency, ω_k is the frequency of photon with the momentum $\vec{k}$ and g_k is the form-factor (coupling constant) and S is quasi-spin. This model was originally solved by V.Weisskopf and E.Wigner in 1930 (see also [9]).

Secondly, it is the models based on a stochastic Liuville equation (see for example a review 10). They describe fluctuations as the Poisson random process with the non-continues trajectories.

The last model is the Anderson-Weiss-Kubo model of phase relaxation. It allows treat local field fluctuations as a random process with the smooth trajectories. Therefore the experimental verification of non-trivial predictions of this outstanding model, pointed out in this paper, could be rather interesting.

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REFERENCES

[1] Yu.Abov, M.Bulgakov, A.Gul'ko et al. ZhETF 99 (1991) 962
[2] F.S.Dzheparov ZhETF 99 (1991) 982
[3] M.I.Bulgakov et al., Pis'ma v ZhETF 58 (1993) 614
[4] P.W.Anderson, P.R.Weiss Rev. Mod. Phys. 25 (1953) 269
[5] R.Kubo J.Phys.Soc Jap. 17 (1962) 1100
[6] V.E.Zobov, A.A.Lundin ZhETF 106 (1994) 1097
[7] F.S.Dzheparov, S.V.Stepanov In "Modern NMR and ESR Methods in Solid-State Chemistry", Chernogolovka (1990) 74
[8] M.I.Bulgakov, A.D.Gul'ko, F.S.Dzheparov, S.S.Trostin In "Problems of Magnetic Resonance", Abstracts of the VII-th All-Union school on magnetic resonance, Slavyanogorsk (1981) p.54
[9] W.Heitler The Quantum Theory of Radiation, Oxford (1954)
[10] I.V.Alexandrov Theory of Magnetic Relaxation, Moscow (1975)