Nutations of spin in the quasi-isotropic superfluid A-like phase of $^3$He.

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Abstract

The order parameter of the quasi-isotropic superfluid A-like phase of $^3$He is rewritten in a simple form. Effect of anisotropy of magnetic susceptibility of this phase on the frequencies of the spatially uniform oscillations of spin and the spin part of its order parameter are found. Anisotropy of susceptibility has pronounced effect on the low-frequency mode, which is analogous to nutations of the asymmetric top. Possibility of observation of the nutation-like mode is discussed.

1 Introduction

The order parameter of the superfluid A-like phase of $^3$He is not yet identified. The measured magnetic susceptibility of the A-like phase coincides with the susceptibility of the normal phase. It means that the A-like phase belongs to the ESP (Equal Spin Pairing) type and its order parameter can be written in a form:

$$A_{\mu j}^{ESP} = \Delta \frac{1}{\sqrt{3}} [\hat{d}_\mu (m_j + in_j) + \hat{e}_\mu (l_j + ip_j)].$$

Here $\hat{d}_\mu$ and $\hat{e}_\mu$ are mutually orthogonal unit vectors, $m_j, n_j, l_j, p_j$ — arbitrary real vectors normalized as: $m^2 + n^2 + l^2 + p^2 = 3$. A-like phase is not ferromagnetic. The minima of the free energy of the bulk (free of impurities) $^3$He in a vicinity of $T_c$:

$$f = f_n + \alpha A_{\mu j}^* A_{\mu j} + \beta_1 |A_{\mu j} A_{\mu j}|^2 + \beta_2 (A_{\mu j} A_{\mu j}^*)^2 + \beta_3 A_{\mu j}^* A_{\nu j} A_{\mu l} A_{\nu l} + \beta_4 A_{\mu j}^* A_{\nu j} A_{\mu l}^* A_{\nu l} + \beta_5 A_{\mu j} A_{\nu j} A_{\mu l} A_{\nu l}^*.$$


corresponding to nonferromagnetic ESP phases were found by Mermin and Stare [2]. There are four such minima (phases): axial (ABM), polar, bipolar and axiplanar. All four order parameters can be represented in a form:

\[ A_{\mu j}^0 = \Delta e^{i\phi} [\hat{d}_{\mu}(v_x \hat{m}_j + iv_y \hat{n}_j) + v_z \hat{e}_{\mu} \hat{l}_j], \]  

where \( \hat{d}_{\mu} \) and \( \hat{e}_{\mu} \) are mutually orthogonal unit vectors in spin space, \( \hat{l}, \hat{m}, \hat{n} \) - three orthonormal vectors in momentum space, \( v_x, v_y, v_z \) - real numbers restricted by the condition: \( v_x^2 + v_y^2 + v_z^2 = 1 \). Every phase is specified by a set of coefficients \( v_x, v_y, v_z \). For the ABM phase these are \( v_x^2 = v_y^2 = 1/2, v_z = 0 \).

In a vicinity of \( T_c \) effect of aerogel on the order parameter can be taken into account phenomenologically by introduction in the Ginzburg and Landau functional of additional term \( \eta_{jl}(r) A_{\mu j} A_{\mu l}^* \). A random symmetric tensor \( \eta_{jl}(r) \) is contracted with the orbital indices of the matrices \( A_{\mu j} \) and \( A_{\mu l}^* \). The order parameters of all phases are continuously degenerate with respect to orbital rotations. According to the general statement of Imry and Ma [3] in that case the interaction \( \eta_{jl}(r) \) disrupts the orientational long-range order. Volovik [4] considered the situation when original order parameter is the ABM. He arrived at the result that the disruption of the orientational long-range order leads to a glass type state with a short-range order described by the ABM order parameter. The resulting ordering is described by the nonvanishing averages \( Q_{\mu \nu jl} = < A_{\mu j}(r) A_{\nu l}^*(r) > \) and according to the Ref. [4] corresponds to a nonsuperfluid spin nematic.

There is an additional effect of aerogel on the superfluid \(^3\)He. The random field \( \eta_{jl}(r) \) induces local fluctuations of the order parameter, which in their turn bring additional contribution to the free energy. As a result the total free energy can have minima, which are different from the listed above. When the contribution of fluctuations is dominating e.g. in a vicinity of \( T_c \), the quasi isotropic (or ”robust”) A-like phase with a long-range, or ”nearly long-range” order becomes a minimum [5]. This phase remains superfluid even when orientational long-range order is disrupted and a glass-like state is formed. The choice between different possibilities depends on concrete parameters of the system, in particular on values of the coefficients \( \beta_1, \ldots, \beta_5 \) in Eq. (2). Because of a lack of precise knowledge of these coefficients even in the bulk \(^3\)He the choice between different possibilities existing in aerogel can not be made on a basis of purely theoretical argument. In such situation for the identification of this phase one has to rely on the comparison of the observed properties of the A-like phase with the predicted theoretically can be of a great importance.

Aerogel effects directly the orbital part of the order parameter of \(^3\)He. The spin part of the order parameter is weakly coupled with the orbital via the
dipole interaction. On the other hand the spin part interacts with magnetic field and directly manifests itself in NMR experiments. These properties make NMR a convenient "probe" of the superfluid state and of its order parameter.

Among the existing NMR data only one experiment [6] makes direct distinction between the ABM and quasi isotropic phase. In that pulsed NMR experiment the dependence of the transverse frequency shift on the tipping angle has been measured. The measured dependence coincides with that predicted for the ”robust” phase [7] and does not coincide with the expected for the ABM phase. The bulk of data of the NMR experiments with the A-like phase in not yet completely understood. In particular the origin of the observed in many experiments negative cw-NMR shift is not clear. In this situation the agreement of one experiment with the theoretical prediction can not be taken as a final proof of the suggested identification. Further experiments would be very useful in making the identification definitive.

A possible experiment could be observation of the low-frequency transverse NMR mode which according to Ref. [7] has to be present in the quasi-isotropic phase but is absent in the ABM phase. In the Ref. [7] the frequencies of the NMR modes were found without account of anisotropy of magnetic susceptibility of the quasi-isotropic phase. It will be shown later that this anisotropy changes substantially the frequency of the above mentioned mode. In the present paper frequencies of all NMR modes for the quasi-isotropic phase are found with account of the anisotropy of susceptibility and a possibility of observation of the low frequency mode is discussed. In comparison with the Ref. [7] calculations are simplified because the order parameter of the quasi-isotropic phase is represented in a more convenient form.

\section{The order parameter}

Quasi-isotropic phases are determined by the condition [5]:

$$\eta_{jl}^{(a)} A_{\mu j} A_{\mu l}^* = 0,$$

(4)

where \(\eta_{jl}^{(a)}\) is an arbitrary real symmetric traceless tensor. Eq.(4) is equivalent to:

$$A_{\mu l} A_{\mu j}^* + A_{\mu j} A_{\mu l}^* = \text{const} \cdot \delta_{ij}.$$  

(5)

The order parameter (1) meets criterion (5) if \(m_j, n_j, l_j, p_j\) satisfy the following equation:

$$m_j m_l + n_j n_l + l_j l_l + p_j p_l = \delta_{jl}.$$  

(6)
The order parameter is degenerate with respect to separate rotations in spin and momentum spaces. For that reason any member of this degenerate family can be chosen as a representative. It has been shown before that the vectors \( \mathbf{m}, \mathbf{n}, \mathbf{l}, \mathbf{p} \) satisfying Eq. (6) have the following property: \( [\mathbf{m} \times \mathbf{n}] \cdot [\mathbf{l} \times \mathbf{p}] = 0 \). That makes possible to introduce three mutually orthogonal unit vectors \( \hat{a}, \hat{b}, \hat{c} \) in the following way: \( \hat{a} \parallel (\mathbf{m} \times \mathbf{n}), \hat{b} \parallel (\mathbf{l} \times \mathbf{p}), \hat{c} = \hat{a} \times \hat{b} \). Only non-ferromagnetic phases will be considered. Expressing \( \mathbf{m}, \mathbf{n}, \mathbf{l}, \mathbf{p} \) in terms of \( \hat{a}, \hat{b}, \hat{c} \) and after straightforward transformations one arrives at:

\[
A_{\mu j}^R = \Delta \frac{1}{\sqrt{3}} e^{i\psi} [\hat{d}_\mu (\hat{b}_j + i \cos \gamma \hat{c}_j) + \hat{e}_\mu (\hat{a}_j + i \sin \gamma \hat{c}_j)],
\]  

(7)

where \( \psi \) and \( \gamma \) are arbitrary angles. Let us express vectors \( \hat{d}, \hat{e} \) in terms of the new vectors \( \hat{d}', \hat{e}' \) obtained by rotation of the pair \( \hat{d}, \hat{e} \) around \( \hat{f} = \hat{d} \times \hat{e} \) for an angle \( \gamma \), and vectors \( \hat{a}, \hat{b}, \hat{c} \) in terms of \( \hat{l}, \hat{m}, \hat{n} \) obtained by rotation of \( \hat{a}, \hat{b} \) around \( \hat{c} \) for \( -\gamma \). The hats are introduced to distinguish the unit vectors \( \hat{l}, \hat{m}, \hat{n} \) from the vectors \( l_j, m_j, n_j \), entering eqns. (3),(4). After the above transformations the order parameter assumes the simple form:

\[
A_{\mu j}^R = \Delta \frac{1}{\sqrt{3}} e^{i\psi} [\hat{d}_\mu (\hat{m}_j + i \hat{n}_j) + \hat{e}_\mu \hat{l}_j].
\]  

(8)

(The primes at \( \hat{d}', \hat{e}' \) are omitted). \( A_{\mu j}^R \) can also be represented in a form (2) with the coefficients \( v_x^2 = v_y^2 = v_z^2 = 1/3 \). Each of the coefficients \( v_x, v_y, v_z \) assumes two values \( \pm 1/\sqrt{3} \). Without magnetic field all combinations of signs yield equivalent order parameters, i.e. transformed into each other by a combination of rotations in spin and orbital spaces. The particular combination of signs, chosen in Eq. (8) in that sense is representative.

3 Nutation mode

It is shown in Ref. [7] that in magnetic field quas-isotropic phase has three modes of small oscillations at the equilibrium configuration: one longitudinal and two transverse. If the Larmor frequency \( \omega_L \) is much greater then the dipole frequency \( \Omega \), and if anisotropy of the magnetic susceptibility is not taken into account, the frequency of one of the transverse modes is close to the Larmor frequency and is of the other \( \Omega^2/\omega_L \).

For the order parameter Eq.(8) in a vicinity of \( T_c \) the magnetic susceptibility tensor has a form:

\[
\chi_{\mu\nu} = \chi_n [\delta_{\mu\nu} - \epsilon(2d_\mu d_\nu + e_\mu e_\nu)],
\]  

(9)

\[ 4 \]
where $\epsilon$ is a positive coefficient $\epsilon \sim (T - T_c)/T_c$. The maximum eigenvalue $\chi_n$ corresponds to the direction $\hat{f} = \hat{d} \times \hat{e}$, i.e. in the equilibrium $\hat{f}$ is parallel or antiparallel to the magnetic field.

The equilibrium configuration of the order parameter in magnetic field and with the account of the dipole interaction was determined before in terms of the vectors $m_j, n_j, l_j, p_j$. Here this configuration is reformulated for the order parameter in the form Eq. (8). Orientation of $\hat{l}, \hat{m}, \hat{n}$ with respect to $\hat{d}, \hat{e}, \hat{f}$ is determined by minimization of the dipole energy:

$$U_D = \frac{\chi_n}{8g^2} \Omega^2 \left[ (\hat{d} \cdot \hat{m} + \hat{e} \cdot \hat{l})^2 + (\hat{d} \cdot \hat{n})^2 + \hat{f} \cdot \hat{n} \right].$$

(10)

Coefficient in front of the energy is expressed in terms of the longitudinal oscillations frequency $\Omega$ and of the gyromagnetic ratio $g$. Minimum of $U_D$ is reached at $\hat{d} \cdot \hat{m} + \hat{e} \cdot \hat{l} = 0, \hat{d} \cdot \hat{n} = 0, \hat{f} \cdot \hat{n} = -1$. According to the last condition $\hat{f}$ and $\hat{n}$ are antiparallel in the equilibrium. Two other conditions determine two possible equilibrium orientations of $\hat{l}, \hat{m}$ with respect to $\hat{d}, \hat{e}$ in a plane perpendicular to $\hat{f}$. These are $\hat{l} = \hat{d}, \hat{m} = -\hat{e}$ and $\hat{l} = -\hat{d}, \hat{m} = \hat{e}$. The dipole interaction lifts the degeneracy with respect to arbitrary rotations of the orbital vectors $\hat{l}, \hat{m}, \hat{n}$ relative to the spin vectors $\hat{d}, \hat{e}, \hat{f}$. Only a discreet two-fold degeneracy is preserved. The discreet degeneracy is analogous to that in the ABM-phase $\hat{l} = \pm \hat{d}$.

Frequencies of cw-NMR are found from the Leggett equations. With the explicit form of the dipole energy (10) and of the susceptibility tensor (9) these equations read as:

$$\dot{S} = S \times \vec{\omega}_L - \frac{\chi_n \Omega^4}{8g^2} \left\{ 2(\hat{d} \cdot \hat{m} + \hat{e} \cdot \hat{l})(\hat{d} \times \hat{m} + \hat{e} \times \hat{l}) + 2(\hat{d} \cdot \hat{n})\hat{d} \times \hat{n} + \hat{f} \times \hat{n} \right\}$$

(11)

$$\dot{\vec{\theta}} = \frac{g^2}{\chi_n} [S + \zeta_1 d\cdot S + \zeta_2 \hat{e} \cdot S] - \vec{\omega}_L.$$  

(12)

Here $\vec{\omega}_L = g H$ and $\dot{\vec{\theta}}$ – the angular velocity of the spin vectors $\hat{d}, \hat{e}, \hat{f}$ i.e. $\dot{\hat{d}} = \dot{\vec{\theta}} \times \hat{d}$ etc.. Tensor of inverse susceptibilities is written as:

$$\chi^{-1}_{\mu \nu} = \frac{1}{\chi_n} [\delta_{\mu \nu} + \zeta_1 d_{\mu} d_{\nu} + \zeta_2 \hat{e}_\mu \hat{e}_\nu],$$

(13)

where $\zeta_1 = 2\epsilon/(1 - 2\epsilon)$ and $\zeta_2 = \epsilon/(1 - \epsilon)$. Linearization of Eqns.(11),(12) at the equilibrium $\hat{f} \parallel H$, $\hat{n} = -\hat{f}$, $\hat{l} = \hat{d}$, $\hat{m} = -\hat{e}$ renders equations for three modes of harmonic oscillations – longitudinal with the frequency

$$\omega^2 = \Omega^2$$

(14)
and two transverse with the frequencies $\omega_\pm$ determined by the equation:

$$2\omega_\pm = \omega_L^2(1 + \zeta_1\zeta_2) + \frac{\Omega^2}{8}(4 + \zeta_1 + 3\zeta_2) \pm \sqrt{[\omega_L^2(1 - \zeta_1\zeta_2) + \frac{\Omega^2}{8}(4 - \zeta_1 - 3\zeta_2)]^2 + \frac{\Omega^4}{16}(\zeta_1 - 3)(1 - 3\zeta_2)}. \quad (15)$$

In the absence of anisotropy of the susceptibility ($\epsilon = 0$), the frequencies (14), (15) coincide with that found before [7].

NMR experiments with the A-like phase are usually performed in magnetic fields for which the condition $\omega_L \gg \Omega$ is met. Expansion over the small ratio $\Omega/\omega_L$ renders less cumbersome expressions for the frequencies of the transverse modes. In zero order on $\Omega/\omega_L$ the frequency $\omega^2_+ = \omega_L^2$, it corresponds to the Larmor precession of spin. The other frequency

$$\omega^2_+ = \omega_L^2\zeta_1\zeta_2 = \frac{\omega_L^2\chi_{ff} - \chi_{dd}}{\chi_{ee}} - \frac{\omega_L^2\chi_{ff} - \chi_{dd}}{\chi_{ee}}, \quad (16)$$

where $\chi_{ff} = \chi_n$ is the maximum, $\chi_{dd}$ and $\chi_{ee}$ - two other principal values of the tensor of magnetic susceptibility, corresponds to the motion of the spin vectors $\hat{d}, \hat{e}, \hat{f}$, which is analogous to nutations of a classical asymmetric top [9]. Taking into consideration further terms of the expansion on $\Omega/\omega_L$ one obtains for the square of the Larmor-like mode:

$$\omega^2_+ = \omega_L^2 + \frac{\Omega^2}{2} - \frac{\Omega^4}{64\omega_L^2} \frac{(3 - \zeta_1)(1 - 3\zeta_2)}{1 - \zeta_1\zeta_2}, \quad (17)$$

i.e. corrections due to the anisotropy of susceptibility start from the terms of the relative order $(\Omega/\omega_L)^4$. For nutation-like mode correction of the order of $\Omega^2$ is:

$$\omega^2_+ = \omega_L^2\zeta_1\zeta_2 + \frac{\Omega^2}{8}(\zeta_1 + 3\zeta_2) + O\left(\frac{\Omega^4}{\omega_L^2}\right), \quad (18)$$

The first two terms in the r.h.s of Eq. (18) disappear when anisotropy tends to zero. The first term disappears also when the maximum principal value of the tensor of magnetic susceptibility coincides with one of the the remaining principal values.

For the pulsed NMR the frequency shift as a function of the tipping angle in a principal order on $\Omega/\omega_L$ can be found with the aid of a standard procedure [10]. Instantaneous orientation of vectors $\hat{d}, \hat{e}, \hat{f}$ is determined by the Euler angles $\alpha, \beta, \gamma$ according to the definition: $\hat{d}(t) = R_x(\alpha)R_y(\beta)R_z(\gamma)\hat{d}_0$, etc., where $\hat{d}_0$ is an equilibrium orientation of $\hat{d}$, and the axes $x, y, z$ are
directed along $\mathbf{d}_0, \mathbf{e}_0, \mathbf{f}_0$ correspondingly. The dipole energy (10) has to be expressed in terms of $\alpha, \beta, \gamma$

$$U_D = \frac{\chi_n}{8g^2} \Omega^2 \left[(1 + \cos \beta)^2 \sin^2(\alpha + \gamma) + \sin^2 \beta \cos^2 \gamma - \cos \beta\right].$$

(19)

and to be averaged over the "fast" variables $\alpha$ and $\gamma$ with the fixed combination $\phi = \alpha + \gamma$. That renders:

$$V = \bar{U}_D = \frac{\chi_n}{8g^2} \Omega^2 \left[(1 + \cos \beta)^2 \sin^2 \phi + \frac{1}{2} \sin^2 \beta - \cos \beta\right].$$

(20)

The pulsed NMR shift $\omega_\perp(\beta) - \omega_L$ is determined by the derivative of $(-V/\chi_n H_0^2)$ over $\cos \beta$ in the minimum of $V$ over $\phi$. The obtained dependence:

$$\omega_\perp(\beta) = \omega_L + \frac{\Omega^2}{8\omega_L} (1 + \cos \beta)$$

(21)

coincides with the obtained before [7].

Unfortunately the observation of the mode (18) is not an easy task. In NMR experiments a motion of magnetization (or spin) is registered. If the dipole energy is neglected spin according to Eqns. (11),(12) precesses with the Larmor frequency irrespective of whether nutations are excited or not. Transverse magnetic field does not interact with the nutations. The coupling is provided only by the dipole interaction. As a result, the intensity of the corresponding line in the NMR spectrum has to be proportional to a power of the ratio $\Omega/\omega_L$. For a quantitative evaluation of this intensity one can apply the expression for absorption of the power $P$ from the r.f. field $\mathbf{H}_1(t) = \mathbf{H}_1 \cos(\omega t)$:

$$P = \frac{1}{4} \omega H_{1\alpha} H_{1\beta} \chi_{\alpha\beta}(-\omega) - \chi_{\alpha\beta}(\omega)].$$

(22)

The answer depends on the polarization of $\mathbf{H}_1(t)$ i.e. on the orientation of the amplitude $\mathbf{H}_1$ with respect to the orbital vectors $\hat{1}, \hat{m}$. For a random orientation of $\hat{1}, \hat{m}$ in the plane, perpendicular to $\mathbf{H}_0$ the trace $\chi_{\alpha\alpha}(\omega)$ enters the expression for intensity. The trace has poles at $\omega = \pm \omega_+$ and $\omega = \pm \omega_-$. The ratio of intensities $I$ of the two lines is determined by the ratio of residues in the corresponding poles:

$$\frac{I_-}{I_+} = \frac{\omega_- \text{Res} \chi_{\alpha\alpha}(\omega_-)}{\omega_+ \text{Res} \chi_{\alpha\alpha}(\omega_+)}.$$

(23)

To find the residues one has to substitute $\mathbf{H}_1(t)$ in Eqns. (11), (12) and to find a linear response to this field. After straightforward calculations one arrives at the expression:

$$\frac{I_-}{I_+} = \frac{(1 + 2\psi)[1 - \zeta_1 \zeta_2 + \psi(4 - \zeta_1 - 3\zeta_2) - R] - \psi^2(6 - \zeta_1 - 9\zeta_2)}{(1 + 2\psi)[1 - \zeta_1 \zeta_2 + \psi(4 - \zeta_1 - 3\zeta_2) + R] - \psi^2(6 - \zeta_1 - 9\zeta_2)}.$$

(24)
Shorthand notations: \( \psi = \Omega^2/8\omega^2 \) and \( R = \{(1 - \zeta_1\zeta_2 + \psi(4 - \zeta_1 - 3\zeta_2))^2 - 4\psi^2(3 - \zeta_1)(1 - 3\zeta_2)\}^{1/2} \) are introduced here. The leading term of the ratio of intensities at \( \psi \ll 1 \) is:

\[
\frac{I_-}{I_+} = \psi^2 \frac{\zeta_1 + 3\zeta_2 - 12\zeta_1\zeta_2 + \zeta_1^2\zeta_2 + 9\zeta_1\zeta_2^2}{2(1 - \zeta_1\zeta_2)^2}.
\]

With account of \( \zeta_1, \zeta_2 \ll 1 \), a simple expression is obtained:

\[
\frac{I_-}{I_+} = \frac{\Omega^4}{128\omega^4 L^4}(\zeta_1 + 3\zeta_2).
\]

It shows, that the relative intensity of the nutation line is going down with the increase of \( \omega_L \). Observation of this mode may become possible in relatively weak fields \( \omega_L \sim \Omega \).

4 Conclusions

The low frequency "nutation" mode is a qualitative distinction of the quasi-isotropic phase from the ABM-phase. In view of the above estimation the absence of the corresponding line in experiments can not be considered as an evidence against the quasi-isotropic phase. In the experiments the condition \( \omega_L \gg \Omega \) has been well satisfied. In that sense NMR experiments with the superfluid \(^3\)He in aerogel in fields \( \omega_L \sim \Omega \) would be useful.

In many experiments with the A-like phase a negative shift of the NMR resonance frequency has been observed. Existence of absorption at frequencies below the Larmor frequency indicates that orientation of the spin triad \( \hat{d}, \hat{e}, \hat{f} \) relative to the orbital \( \hat{l}, \hat{m}, \hat{n} \) does not correspond to a minimum of the dipole energy. Deviation from the minimum can occur because of a presence of singularities of the order parameter, in particular of domain walls. Possible structures of the domain walls depend on the order parameter. In the ABM-phase there are walls across which the relative orientation of the vectors \( \hat{d} \) and \( \hat{l} \) changes from \( \hat{d} \parallel \hat{l} \) to \( \hat{d} \parallel (-\hat{l}) \). In the quasi-isotropic phase there are analogous domain walls with a continuous transition between two minima of the dipole energy: \( \hat{l} = \hat{d}, \hat{m} = -\hat{e} \) and \( \hat{l} = -\hat{d}, \hat{m} = \hat{e} \).

In a presence of magnetic field the quasi-isotropic phase has additional type of the domain wall. The maximum principal value of the magnetic susceptibility corresponds to the direction \( \hat{f} \). In magnetic field \( H \) it is possible to have domains with the different orientation of \( \hat{f}: \hat{f} \parallel H \) and \( \hat{f} \parallel (-H) \), separated by the domain wall with a thickness \( \xi_H \sim c/\omega_L \), where \( c \) is the spin wave velocity. Minimum of the dipole energy is reached at \( \hat{m} \parallel -\hat{f} \).
The orbital triad $\hat{l}, \hat{m}, \hat{n}$ is adjusted to the spin in a layer of the thickness $\xi_D \sim c/\Omega$. Within this layer mutual orientation of the spin and the orbital vectors does not correspond to a minimum of the dipole energy.

Both in the ABM and in the quasi-isotropic phase there are reasons for the negative shift of the NMR-line. Different defects manifest themselves in different shapes of the NMR-line, but interpretation of the influence of defects requires rather involved analysis and is not direct. The resulting conclusions based on such interpretation are not as convincing as that based on interpretation of NMR spectra of the uniform liquid.

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