SPIN-SPIN PARAMAGNETIC RELAXATION TIME IN THE ABSENCE OF A STATIC MAGNETIC FIELD FOR $Co(NH_4)_2(SO_4)_2 \cdot 6H_2O$ *AT HELIUM TEMPERATURES*

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UNTIL now, the spin-spin paramagnetic relaxation time τ_{ss} in magnetically anisotropic monocrystals has been calculated theoretically only for some substances which contain magnetically equivalent ions.[1] In single crystals with magnetic ions situated in diverse intracrystalline electric fields E, the relaxation process has a more complex character. The time τ_{ss}, generally speaking, does not have extrema along the principal axes K_1, K_2 and K_3 (reference 2) of the static magnetic susceptibility tensor χ_0, and in case of strong anisotropy of the g factors, the value of τ_{ss} can vary within wide limits. Calculations were carried out by us under the following assumptions: (1) The spin-system consists of an equal number of ions of two sorts. (2) In the absence of the static magnetic field H_0, the ground state of all the ions has twofold Kramers degeneracy. (3) The spin temperature T is so low that only the principal doublet is occupied, i.e., the effective spin is $S = \frac{1}{2}$ for all the ions. (4) The interactions in the paramagnets can be described by means of the two-particle $P^{ik}_{\gamma\delta}\sigma^i_\gamma\sigma^k_\delta$ and one-particle $\frac{1}{2}A^k_{\gamma\delta}\sigma^k_\gamma I_\delta$ tensor operators, where σ^i_γ is a Pauli matrix, I_δ is a matrix spin-vector, and k and δ are indices which label the particles and the coordinate axes respectively. In the calculations it was supposed that the principal axes of the tensors P and A do not coincide with one another, and that the g tensors pertaining to different type ions have different forms. (5) The aperiodic curve $f(\nu)$ (where ν is the frequency of the applied magnetic field H_t)[3] of paramagnetic absorption has a gaussian shape at $H_0 = 0$.

Taking into account conditions 1 to 4, we obtained a formula for the tabulated second moment[3] $\langle\nu^2\rangle$ of the curve $f(\nu)$ for arbitrary direction of the field H_t relative to the principal axes of the tensor χ_0. The theoretical value for $\langle\nu^2\rangle$ can be directly compared with the experimental data. If condition 5 is satisfied, $\langle\nu^2\rangle$ can be used for the calculation of τ_{ss} according to Broer's formula:[3] $\tau_{ss} = [\pi/2\langle\nu^2\rangle]^{1/2}$. The components of the tensors P and A, which determine the quantity $\langle\nu^2\rangle$, also enter into the formulas for χ_0, the magnetic specific heat C_0 (reference 2), and the paramagnetic resonance line breadth $\Delta H_{1/2}$.[1] Our formulae thus establish a connection between $\langle\nu^2\rangle$, τ_{ss}, χ_0, C_0 and $\Delta H_{1/2}$.

Specific calculations have been carried out for $Co(NH_4)_2(SO_4)_2 \cdot 6H_2O$ at helium temperatures. In this case, P characterizes the dipole-dipole ($\mathcal{H}_d$) and exchange ($\mathcal{H}_{ex}$) interactions; A characterizes the hyperfine spin interaction $\mathcal{H}_{hfs}$ between the nucleus and the unpaired electrons within one and the same paramagnetic ion. The numerical values of the components of the tensor A along the principal axes were taken by us from reference 4 and pertain to Co^{59}. In the calculation of the components $P^{ik}_{\gamma\delta}$ we used the values of the g factors and the true eigenfunctions of the fundamental Kramers doublet given in references 4 and 5 respectively. The lattice sums, which enter in $\langle\nu^2\rangle$, were evaluated by means of the tables compiled in references 2 and 6. We evaluated the exchange integrals J_1 and J_2, between the nearest and next nearest neighbors of a paramagnetic ion respectively, by means of formulae from reference 6. Upon correction of one arithmetical error in the derivation of these formulae, we obtained $J_1/k = 0.017°$ and $J_2/k = -0.0104°$, where k is Boltzman's constant.

The table lists the results of calculations of $\langle\nu^2\rangle \times 10^{-18}$ sec^{-2} and of τ_{ss} sec for the directions K_1, K_2, K_3, and ϵ, where ϵ is the axis of symmetry of the field E for one of the non-equivalent ions and $\langle\nu^2\rangle_d$, $\langle\nu^2\rangle_{ex}$, $\langle\nu^2\rangle_{hfs}$ and $\langle\nu^2\rangle_{d-ex}$ are additive contributions due to

	$\langle\nu^2\rangle_d$	$\langle\nu^2\rangle_{ex}$	$\langle\nu^2\rangle_{d-ex}$	$\langle\nu^2\rangle_{hfs}$	τ_{ss}
$H_t \parallel K_1$	334	33	−110	30	$7.4 \cdot 10^{-10}$
$H_t \parallel K_2$	616	217	70	283	$3.75 \cdot 10^{-10}$
$H_t \parallel K_3$	527	−99	237	12	$4.81 \cdot 10^{-10}$
$H_t \parallel \epsilon$	256	33	−93	25	$8.43 \cdot 10^{-10}$

$\mathcal{H}_d$, $\mathcal{H}_{ex}$, $\mathcal{H}_{hfs}$ and the dipole-exchange interactions, respectively.

In conclusion, the author expresses his thanks to Prof. S. A. Al'tshuler for suggesting the topic and for his interest in the work.

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ON THE THEORY OF COMPOSITE π^0 MESONS

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IT is generally acknowledged today that the π mesons spend part of their time in the form of a baryon-antibaryon pair, i.e., the π mesons are represented at least part of the time (and in the model of Fermi and Yang,[1] all the time) as a tightly bound nucleon-antinucleon pair. If we require the π mesons to form an isotopic triplet, we obtain

$$\pi^+ = p\bar{n},\ \pi^0 = (p\bar{p} + n\bar{n}) / \sqrt{2} = (\pi_1 + \pi_2) / \sqrt{2},\quad \pi^- = n\bar{p}. \tag{1}$$

Recently, the possibility also of the existence of an isotopic singlet was noted.[2,3] In the theory of composite particles this is represented as

$$\rho^0 = (p\bar{p} - n\bar{n}) / \sqrt{2} = (\pi_1 - \pi_2) / \sqrt{2}. \tag{2}$$

Obviously, the Coulomb interaction in the $\pi_1 = p\bar{p}$ compound will result in different properties for the π_1 and π_2 mesons.

Following Zel' dovich,[4] it is easy to show that the masses of the π_1 and π_2 compounds are different:

$$\Delta M = m_{\pi_2} - m_{\pi_1} = c^{-2} \langle W_{\text{el-mag}} \rangle_{\text{av}} = (e/c)^2 \langle -r^{-1} \rangle_{\text{av}} = 12.7\, m_e, \tag{3}$$

where m_e is the electron mass. The averaging is over the wave function found by Fermi and Yang.[1] It is clear that the life times of these compounds will also be different. Thus, according to the calculations of Romankevich, which use lowest-order perturbation theory,[5]

$$\tau(\pi_1) / \tau(\pi_2) = (3/\pi^2)(g^2/\hbar c)^2$$

($g^2/\hbar c$ is the dimensionless coupling constant for the coupling of the π meson field with the nucleons). Therefore, if initially the beam contains only π^0 mesons and if the corresponding wave function has the form $\Psi(0) = (\pi_1 + \pi_2)/\sqrt{2}$, then the amplitudes for the states π_1 and π_2 at time t will not be equal, and

$$\Psi(t) = \{\pi_1 \exp[-t/2\tau(\pi_1) + i\omega_1 t] + \pi_2 \exp[-t/2\tau(\pi_2) + i\omega_2 t]\} / \sqrt{2}, \tag{4}$$

where $\hbar\omega_i = c\sqrt{p^2 + m_i^2 c^2}$.

Thus it is possible that the relative phase of the states π_1 and π_2 changes, i.e., we have the possibility of the transition of the π^0 meson into a ρ^0 meson in real or, at least, virtual (when the mass of ρ^0 is greater than the mass of π^0) processes.

In the calculation of the probability for finding the π^0 or the ρ^0 mesons we can neglect the strongly oscillating term containing $\cos(c^2\Delta Mt/\hbar)$, since, according to (3), $c^2\Delta M/\hbar \sim 10^{-21}\ \text{sec}^{-1}$. Normalized for one particle, the probability for finding either meson has the form:

$$P(\pi^0 t) = P(\rho^0 t) = \tfrac{1}{4}\{\exp[-t/\tau(\pi_1)] + \exp[-t/\tau(\pi_2)]\},$$

i.e., our calculations lead to a decay scheme for the π^0 meson which is characterized by the sum of two exponentials.

Thus, according to the proposed scheme, π^0 and ρ^0 mesons participate in strong interactions, where the total isotopic spin is conserved, and π_1 and π_2 mesons participate in electromagnetic and weak interactions.

We do not exclude the possibility that the difference in the life times of the mesons emitted in different processes is connected with precisely this circumstance. For π^0 mesons produced in nucleon-nucleon collisions (strong interaction) $\tau \sim 5 \times 10^{-15}$ sec (reference 6), and for π^0 mesons arising in the K-meson decay (weak interaction), $\tau \lesssim 5 \times 10^{-16}$ sec (reference 7). According to our