

*Mechanism of  $\mu$ -Meson Depolarization in Molecular Condensed Media*

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The effect of rapid chemical mesic atom reactions on depolarization of the negative muon is considered on the basis of the concept of a "Coulomb explosion" resulting from the high ionization of the molecule in Auger transitions in the mesic atom. It is shown that the experimental dependence of residual muon polarization on temperature in the case of atom capture by water corresponds to the mean time required for the mesic atom produced to participate in the chemical reaction, this being  $(8.3 \pm 1.2) \cdot 10^{-12}$  sec at 80°K and  $(2.5 \pm 0.4) \cdot 10^{-12}$  sec at 273°K.

A considerable number of experimental investigations of the depolarization of negative muons in different media have been performed by now. A detailed bibliography is given in a paper by one of the authors.<sup>[1]</sup> An analysis of the experimental data shows that the depolarization of a muon captured by a given atom depends significantly on the structure of the molecule containing this atom. Thus, for example, when muons are captured by oxygen in water<sup>[2,3]</sup> and in liquid oxygen,<sup>[3]</sup> the asymmetry coefficients of the  $\mu^- \rightarrow e^-$ -decay electrons are respectively  $(1.7 \pm 0.5)\%$  and  $(0.4 \pm 0.5)\%$ . Such a difference cannot be explained from the point of view of the theory of cascade depolarization,<sup>[4,5]</sup> which gives for the residual polarization on the K shell of the mesic atom a value equal to one-sixth of the initial muon polarization. However, no theoretical investigations aimed at explaining the depolarization mechanisms in real media have been performed to date.

It was proposed in<sup>[1]</sup> that a possible mechanism influencing the depolarization, in addition to the cascade mechanism, may be the interaction between the mesic atom and the surrounding medium, and the chemical bonding of this atom with the molecules of the surrounding medium. It was thus proposed to explain the residual polarization in water as being due to the reactions between the water molecules and the mesic radical of nitrogen (the mesic atom of oxygen in the electronic ground state has an electron shell  $1S^2 2S^2 2P^3$ ; owing to the screening of one charge unit of the nucleus by the muon, such an electronic structure corresponds to a nitrogen atom, and we shall henceforth call such a system mesic nitrogen or the mesic radical of nitrogen). However, chemical reactions between thermalized mesic nitrogen and water are energy-forbidden. Moreover, they are forbidden even if account is taken of the recoil energy of the mesic atom ( $\sim 1$  eV), which this atom can acquire upon emission of a quantum of mesic x-radiation. Nonetheless, the fact that one observes in experiment<sup>[2,3]</sup> the precession of the free spin of the meson in a transverse field, and not of the summary magnetic moment of the paramagnetic mesic nitrogen, indicates that it is necessary to take into account rapid chemical interactions of the mesic nitrogen, since only they can lead to a compensation of the unpaired electrons and to elimination, by the same token, of the paramagnetism of the electron shell. Consequently, for a correct solution of the problem it is necessary to make use of some ad-

ditional processes that occur when a muon is captured by an atom of the medium and which permit the mesic radical to enter into a chemical bond. The present paper is devoted to an attempt at such an analysis, using the capture of a muon in water as an example.

When a negative muon slows down in matter, it is captured in a bound state. Since the capture proceeds predominantly via the Auger mechanism,<sup>[6]</sup> it is natural to assume that the muon "lands" in the region of maximum electron density, i.e., on the average at a level in the region  $n \sim (m_\mu/m_e)^{1/2} \approx 14-15$ .<sup>[7]</sup> This, however, does not exclude the possibility of landing on higher-lying levels. To determine the population with respect to the principal quantum number  $n$ , it is necessary to know the slowing-down mechanism (in the low-energy region) and the dependence of the cross section for capture at a level with given  $n$  on the meson energy. If only thermalized mesons are captured, as is considered in the model of large mesic molecules,<sup>[8]</sup> then the possibility of landing in some region is proportional to the density of the electrons in this region. It follows from such an assumption that, for example, in the water molecule,  $\approx 20\%$  of all the muons land in the region of the valence electrons. For such levels,  $n \geq 30$ . In the remaining cases, the muon lands immediately on separated levels for which  $n < 30$ , and only such cases will be considered, while the contribution to the residual polarization from the muons that land on the common molecular levels will be neglected.

For muons captured by the separated levels, the usual cascade of Auger and radiative transitions takes place. Since the probability of the radiative transitions decreases with increasing principal quantum number  $n$  ( $\Gamma_{\text{rad}} \sim n^{-3}$ ), and the probability of the Auger transitions, to the contrary, increases with increasing  $n$ , the probability of the Auger transitions greatly exceeds the probability of the radiative transitions at the high-lying levels of the mesic atom. According to estimates by Burbidge and de Borde,<sup>[9]</sup> the ratio of the rates of the Auger transitions and of the radiative transitions in the region of light nuclei  $Z \leq 10$ , is as follows for  $n \geq 8$ :  $\Gamma_{\text{Auger}}/\Gamma_{\text{rad}} \geq 10^5$ , and the rates of the Auger transitions are of the order of  $10^{15}-10^{16}$  sec<sup>-1</sup>. According to estimates by the same authors, the probability of ejecting all the electrons of the atom by Auger transitions is large for light nuclei.

What happens if the muon is captured by an atom con-

tained in the molecule? If the Auger transitions lead to partial or complete disintegration of the electronic shells of all atoms, then this causes an intense Coulomb decay of the molecule. Indeed, such a situation takes place, for example, when a vacancy is produced in the K shell of the iodine in the  $\text{CH}_3\text{I}$  molecule. Karlson and White<sup>[10]</sup> observed in their experiment H, C, and I ions with charge and energy values that can be attributed only to fast and complete disintegration (as a result of autoionization) of the valence band of all the atoms. The average ion energies correspond to the energy of the Coulomb repulsion "Coulomb explosion" under the assumption that the disintegration of the electron shells occurs during a time much shorter than the time for the ions to move apart, i.e., within a time  $\leq 10^{-15}$  sec. This means that the "mobility" of the valence electrons in the molecule is very large. The effect of the "Coulomb explosion" was observed in many molecules (see also<sup>[11]</sup>).

Thus, when a muon lands at a level with  $n \approx 14-15$  of the mesic oxygen atom of the water molecule, all the electrons of the molecule can actually be ejected via Auger transitions by the time the muon reaches the level  $n \approx 5-6$ . The energy of the Auger electrons will lie in the interval from  $10^2$  to  $10^3$  eV. Such electrons are capable of producing "bore holes"<sup>[12]</sup> distributed isotropically around the mesic atom. In each such "bore holes" there can be located up to six pairs of H and OH radicals.<sup>[13]</sup>

Starting from the universally assumed model of the water molecule (see, for example,<sup>[14]</sup>) it is easy to calculate the energy of the "Coulomb explosion" in the case of total stripping of the electrons from the molecule. This energy is approximately 220 eV, and is entirely carried away by the produced protons, since they move apart at an angle close to  $\pi$ . As they slow down, the protons form a zone saturated with fragments of the water molecule, namely the radicals H and OH. A rough estimate, using the Libby mechanism for the production of radicals,<sup>[15]</sup> shows that on the average approximately 10 pairs of H and OH radicals are produced in the zone in which protons with energy 100 eV are slowed down. These radicals then begin to be combined with production of molecular products and to diffuse from the reaction volume (the volume in which all the produced radicals are situated). The quantitative interpretation of such phenomena is very complicated. It is carried out by the methods of diffusion kinetics (see, for example,<sup>[13]</sup>).

The production of the radicals proceeds in parallel with the thermalization of the mesic atom, which acquires an electron shell as it slows down in the collisions with the surrounding medium. The recombination energy is released rapidly ( $< 10^{-13}$  sec) by emission of  $\gamma$  quanta via the impact mechanism. The time of acquisition of the electrons is comparable with the time of collision of the molecules in the water, i.e., on the order of  $10^{-13}$  sec. The mesic nitrogen in the ground state, which is produced in this manner, has a term  $S_{3/2}$ . This means that the orbital angular momenta of all three electrons are compensated, and the spins become parallel to one another.

If we disregard the subsequent interactions of the mesic nitrogen with the surrounding medium, including

the produced radicals, which lead to compensation of the unpaired electrons, then further depolarization is possible as a result of spin-flip transitions between the hyperfine structure states as a result of the interaction of the spin of the muon on the K shell with the angular momentum of the electron shell.<sup>[4]</sup> When this mechanism is taken into account, the residual polarization  $P$  is given by the expression

$$P = P_0 F, \quad (1)$$

where  $P_0$  is the polarization at the instant of termination of the mesic-atom cascade, and

$$F = \frac{1}{3} \left( 1 + \frac{2}{(2J+1)^2} \right), \quad (2)$$

$J$  is the total angular momentum of the electron shell. The physical meaning of  $F$  is that total depolarization occurs in  $1 - F$  cases, but not in the remaining ones. Numerically  $F$  varies from  $\frac{1}{2}$  to  $\frac{1}{3}$ . The frequency  $\nu$  of the meson spin flip as a result of the hyperfine interaction can be determined from the relation<sup>[16]</sup>

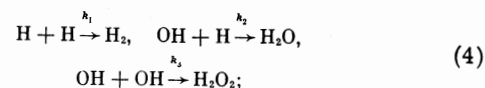
$$\nu = \frac{W_{\text{hfi}}}{\hbar}, \quad W_{\text{hfi}} \approx \frac{32}{3} \frac{\mu_\mu \mu_e}{\hbar r^3}; \quad (3)$$

Here  $W_{\text{hfi}}$  is the energy of the hyperfine interaction,  $\mu_\mu$  and  $\mu_e$  are the magnetic moments of the muon and of the electron shell, and  $r$  is the radius of the paramagnetic shell. Such a calculation, for the  $S_{3/2}$  state of mesic nitrogen, yields a spin-flip frequency  $\nu \approx 2.1 \times 10^{11}$  sec<sup>-1</sup>.

Since the residual polarization is usually measured in experiments by the method of precessing the meson spin in a transverse magnetic field, then it is necessary to take into account also the apparent depolarization due to the precession of the summary magnetic moment of the electron shell and of the muon. The frequency  $\Omega$  of such a precession is larger by approximately two orders of magnitude than the frequency  $\omega$  of the precession of the free spin of the meson. For example, in a transverse field of 50 G the frequency is  $\Omega \approx 1.3 \times 10^9$  sec<sup>-1</sup>, whereas  $\omega \approx 5 \times 10^6$  sec<sup>-1</sup>, so that by the time the registration of the decay electrons begins ( $\sim 10^{-7}$  sec) there should occur a complete depolarization of the muon at the frequency of its spin precession. These are the two muon depolarization mechanisms acting after the end of the mesic-atom cascade and after the mesic atom has acquired an electron shell.

The reactions between the mesic nitrogen and the radicals produced in the "bore holes" of the Auger electrons and during the deceleration of the fragments of the "Coulomb explosions" are regarded in the present article as the reason why the residual polarization in water, measured by the method of precession at the frequency of the free spin of the muon, differs from zero.

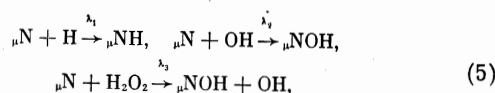
Let us consider the interaction of the H and OH radicals with each other and with the mesic nitrogen. We write down the most important reactions



here  $k_1$ ,  $k_2$ , and  $k_3$  are the rate constants of the corresponding chemical reactions. It is known from the pub-

lished data<sup>[12]</sup> that reactions with formation of molecular products occur very rapidly ( $10^{-12}$ – $10^{-11}$  sec) in the liquid and solid phases, owing to the large concentrations of the radicals produced, for example, as a result of deceleration of a heavy particle. This occurs because the work necessary to move the radicals from the heated zone into the condensed phase is large. For example, even for liquid water<sup>[13]</sup> the recombination processes are significant only in the interval from  $10^{-12}$  to  $10^{-10}$  sec, and from  $10^{-10}$  to  $10^{-8}$  sec the concentration of the radicals and of the molecular products is practically constant. We shall therefore assume that by the time when the reactions in which the mesic nitrogen takes part begin to play an important role, the concentration of the radicals and of the molecular products becomes already practically independent of the time. The concentration of the radicals should not depend on the temperature of the medium, because recombination processes begin in the region heated<sup>[17]</sup> by the "Coulomb explosion," where the temperature is much higher than the temperature of the medium. The temperature in the medium assumes an important role at a later stage, after the zone cools down, when reactions of the radicals and the molecular products with impurities (in our case with the mesic atoms) become significant.

As the most important reactions of the mesic nitrogen with the radicals H and OH and with the molecular products, let us consider the reactions



where  $\lambda_1$ ,  $\lambda_2$ , and  $\lambda_3$  are the constants of the chemical reactions of mesic nitrogen with the corresponding radical or molecular product. We shall not consider sequential or multiparticle reactions, since their contribution is much smaller in the time interval under consideration ( $10^{-9}$ – $10^{-12}$  sec), or in any case within a time comparable with the time of the spin flip as a result of the hyperfine interaction.

Let us write down a differential equation for the rate of entry of the mesic nitrogen into the chemical reaction:

$$-\frac{d}{dt} [\mu\text{N}] = \lambda_1 [\mu\text{N}] [\text{H}] + \lambda_2 [\mu\text{N}] [\text{OH}] + \lambda_3 [\mu\text{N}] [\text{H}_2\text{O}_2] = [\mu\text{N}] \{ \lambda_1 [\text{H}] + \lambda_2 [\text{OH}] + \lambda_3 [\text{H}_2\text{O}_2] \}. \quad (6)$$

The expressions in the square brackets denote the concentrations of the corresponding products. We introduce the notation

$$\lambda_0 = \lambda_1 [\text{H}] + \lambda_2 [\text{OH}] + \lambda_3 [\text{H}_2\text{O}_2], \quad (7)$$

where  $\lambda_0$  is the reciprocal of the time of entry of the mesic nitrogen into the chemical reaction. Solving the foregoing equation for  $[\mu\text{N}]$ , we obtain for the reaction rate

$$-\frac{d}{dt} [\mu\text{N}] = [\mu\text{N}]_0 \lambda_0 e^{-\lambda_0 t}. \quad (8)$$

The rate of the reaction at a given instant of time determines the probability  $w_N$  of the reaction. For the purpose of normalization, we shall consider the reactions only in the reaction volume  $V_r$ . Then, starting from the fact that only one mesic-nitrogen atom is located in this

volume, i.e.,

$$[\mu\text{N}]_0 = 1/V_r, \quad (9)$$

the probability that the mesic nitrogen will enter into chemical reaction at the instant of time  $t$  can be written in the form

$$w_N(t) = \lambda_0 e^{-\lambda_0 t}. \quad (10)$$

The precession at the frequency  $\omega$  can be observed, as already mentioned, only when the mesic nitrogen forms a diamagnetic compound. Obviously, the probability  $w_N^d$  of formation of a diamagnetic product can be written in the form

$$w_N^d(t) = \lambda e^{-\lambda t}, \quad (11)$$

here  $\lambda$  is the reciprocal of the time of entry of the mesic atom into the chemical reaction with formation of a diamagnetic product.

Let us see now how the entry of the mesic atom into the chemical reaction influences the muon depolarization. In the muon spin precession method, one measures in the experiment the time distribution of the decay electrons

$$N_e(t) = N_0 e^{-t/\tau} \{ 1 + B \cos(\omega t + \varphi) \}; \quad (12)$$

here  $N_e(t)$  and  $N_0$  are the electron counts at the instant of time  $t$  and at zero time, respectively,  $\tau$  is the muon lifetime in the given mesic atom,  $B$  is the observed asymmetry coefficient, and  $\varphi$  is the initial phase of the precession at the frequency  $\omega$ . The second term in the curly brackets (which we denote by  $x(t)$ ) represents the precession of a vector whose direction is given by the magnetic moment of the muon, and whose absolute magnitude is equal to the asymmetry coefficient of the decay electrons. The quantity  $B$  is the result of averaging (over the time of entry of the mesic nitrogen into the chemical reaction) of the asymmetry coefficient  $B_0$  corresponding to the polarization  $P_0$ , and the expression for  $x(t)$  in the case of apparent paramagnetic depolarization is given by

$$x_i(t) = B_0 \overline{\cos(\omega t + \Omega t_i)}; \quad (13)$$

here  $t_i$  is the time of entry of the mesic atom into the chemical reaction with formation of any diamagnetic product. Thus, the term  $\Omega t_i$  is the initial phase of the precession for each individual act of chemical reaction.

In accord with the definition of the mean value we have

$$x_i(t) = B_0 \frac{\lambda}{\lambda_0} \int_0^T \cos(\omega t + \Omega t_i) w_N(t_i) dt_i / \int_0^T w_N(t_i) dt_i, \quad (14)$$

where  $T$  and  $t$  are respectively the starting and running times of the observation of the decay electrons. Under the condition that there is no free mesic nitrogen left by the start of the observation, i.e., if  $\lambda_0 T \gg 1$ , we obtain

$$x_i(t) = B_1 \cos(\omega t + \varphi_0). \quad (15)$$

Here

$$B_1 = B_0 \frac{\lambda}{\lambda_0} \left[ 1 + \left( \frac{\Omega}{\lambda_0} \right)^2 \right]^{-1/2}, \quad \varphi_0 = \arctg \frac{\Omega}{\lambda_0}; \quad (16)$$

$B_1$  is the asymmetry coefficient and  $\varphi_0$  is the initial

phase of the precession of the free (free as a result of the chemical reaction), spin of the meson with frequency  $\omega$ , corresponding to the transverse magnetic field  $H_{\perp}$ .

As already shown above, such a mechanism of apparent paramagnetic depolarization acts in a fraction  $F$  of the cases (in the case of mesic nitrogen,  $J = \frac{3}{2}$  and  $F = 37.5\%$ ). In the remaining  $1 - F$  cases, when the depolarization is due to the hyperfine interaction of the magnetic moment of the muon and the electron shell of the mesic radical, we can write for the precession of the magnetic moment of the muon

$$x_2(t) = B_0 f(t_1/\nu) \cos \omega t, \quad (17)$$

where  $f(t_1/\nu)$  is a function of the transition frequency between the levels of the hyperfine structure  $\nu$  and the time of entry into the chemical reaction with formation of a diamagnetic product. The function  $f(t_1/\nu)$  is such that if the integer part of  $t_1/\nu$  is even, then  $f(t_1/\nu) = +1$ , and if it is odd, then  $f(t_1/\nu) = -1$ . The precession of the spin of the free muon can then be written in the form

$$x_2(t) = B_2 \cos \omega t. \quad (18)$$

Here

$$B_2 = B_0 \frac{\lambda}{\lambda_0} \text{th} \frac{\lambda_0}{2\nu} \quad (19)$$

is the asymmetry coefficient of the decay electrons in depolarization due to the hyperfine interactions, which operates in  $1 - F$  cases (62.5% for mesic nitrogen).

As a result of the action of both mechanisms, one observes in the experiment a summary precession with amplitude equal to  $B$ :

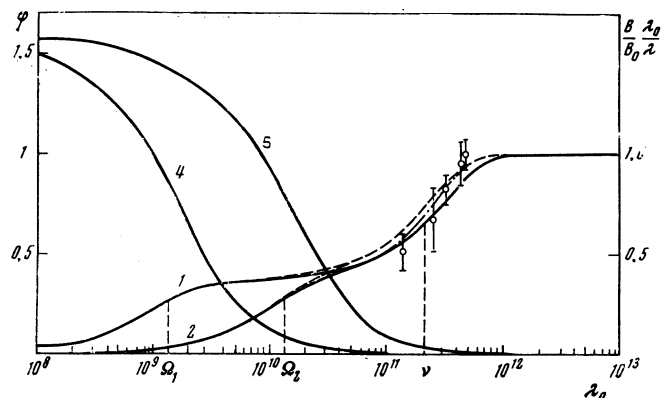
$$B = [F^2 B_1^2 + (1 - F)^2 B_2^2 + 2F(1 - F)B_1 B_2 \cos \varphi_0]^{1/2} \quad (20)$$

and with an initial phase determined from the relation

$$\text{tg} \varphi = \frac{F B_1 \sin \varphi_0}{(1 - F) B_2 + F B_1 \cos \varphi_0}. \quad (21)$$

The figure shows a plot of the relative value of the asymmetry coefficient  $B\lambda_0/B_0\lambda$  and of the initial precession phase  $\varphi$  against the value of  $\lambda_0$ , which is the reciprocal of the time of entry of the mesic nitrogen into the chemical reaction, for two values of the magnetic field intensity, corresponding to the precession frequencies  $\Omega_1$  and  $\Omega_2$  of the summary magnetic moment. We see that at least two reference points are of importance for the determination of the time of entry of the mesic atom into the chemical reaction: these are the reciprocals of the frequencies  $\Omega$  and  $\nu$ . As seen from the figure, the initial phase of the precession is sensitive to the variation of the magnetic field intensity if the time of entry of the mesic atom into the chemical reaction is larger than  $\sim 10^{-11}$  sec, and the relative value of the asymmetry coefficient is sensitive to this variation if this time is  $\geq 5 \times 10^{-11}$  sec. It was assumed earlier that the concentration of the radicals does not change with time. If it is assumed that in the time interval from  $10^{-10}$  to  $10^{-12}$  sec the concentration of the radicals and of the molecular products changes by not more than 1.5 times,<sup>[13]</sup> then the obtained curve, shown in the figure by the dashed line, should be regarded as the limiting curve.

The presented dependence of the relative value of the decay-electron asymmetry coefficient on the time of entry of the mesic nitrogen into the chemical reaction of the muon can be compared with the experimentally obtained<sup>[2]</sup> temperature dependence of the asymmetry coefficient. We consider only the section of this dependence for temperatures below 273°K. Experiment shows that when the temperature of ice changes by an approximate factor 3.5, i.e., from the melting point of ice (273°K) to the boiling point of nitrogen ( $\sim 80^\circ\text{K}$ ), the residual polarization of the muon changes by an approximate factor of 2, and the relative value of the residual polarization, expressed in units of  $B(T)/B_C$ , where  $B(T)$  is the asymmetry coefficient of the decay electrons in water at the temperature  $T$  and  $B_C$  is the asymmetry coefficient in graphite (the asymmetry coefficient observed in graphite is the largest for all the investigated substances) changes with increasing temperature from  $\sim 0.2$  to  $\sim 0.4$ . If it is assumed that the rate of the radical-radical chemical reactions is proportional to the temperature,<sup>[18]</sup> then a change in this rate by a factor 3.5 leads to a like change in the average time of entry into the chemical reaction. There are approximately two sections with this slope on the presented plot. The first (near  $\Omega_1$  or  $\Omega_2$ ) is due to the competition of the apparent paramagnetic depolarization, and the second (near  $\nu$ ) is due to the competition of the depolarization caused by the hyperfine interaction with the rate of entry of the mesic nitrogen into the chemical reaction with formation of a diamagnetic product. If we mark on the figure the relative values of the residual polarization for different temperatures, such that the ratio of the values of  $\lambda_0$  for the two extreme values of the temperature is also equal to 3.5, then the experimental values agree sufficiently well with the slope of the theoretical curve in the two sections pointed out above. From a comparison of the experimental data with the calculated curve it follows that the section of the temperature



Relative value of the asymmetry coefficient  $B\lambda_0/B_0\lambda$  of the electrons from the  $\mu^- \rightarrow e^-$  decay and initial phase  $\varphi$  of the precession at the frequency of the free spin of the muon vs. the reciprocal  $\lambda_0$  of the time of entry of the mesic nitrogen into the chemical reaction. Curve 1—plot of  $B\lambda_0/B_0\lambda$  against  $\lambda_0$  for  $H_{\perp} = 50$  G, curve 2—the same for  $H_{\perp} = 500$  G; curve 3—plot of  $\varphi$  against  $\lambda_0$  for  $H_{\perp} = 500$  G, curve 4—the same for  $H_{\perp} = 50$  G. The dashed line is drawn under the assumption that the radical concentration changes by a factor 1.5 in the time interval from  $10^{-12}$  to  $10^{-10}$  sec; dash-dot line—the same for the interval  $10^{-12}$ – $10^{-11}$  sec. The experimental values were taken from [2] and normalized to the curve; the normalization coefficient is equal to 2.6.

dependence from 80 to 273°K fits satisfactorily to the following intervals of values of the average time of entry into the chemical reaction:  $\Delta t_{\nu} \approx 7 \times 10^{-12} - 2 \times 10^{-12}$  sec or  $\Delta t_{\Omega} \approx 1.5 \times 10^{-9} - 4.3 \times 10^{-10}$  sec for  $H_{\perp} = 50$  G.

Naturally, a unique choice between these two solutions becomes possible through an experimental investigation of the dependence of the residual polarization and of the phase of the precession on the value of  $H_{\perp}$ . In the case when the first solution is realized ( $\Delta t_{\nu}$ ) the dependence of the residual polarization on  $H_{\perp}$  should be practically nonexistent, and the initial phase of the precession should be small. One can attempt, however, to give preference to one of the solutions, if one compares the absolute values (or the values relative to graphite) of the residual polarization in water with the calculation, using certain assumptions for the estimate of  $B\lambda_0/B_0\lambda$ . Thus, it can be assumed that  $B_0$  coincides with the value measured for the case of graphite, and  $\lambda_0/\lambda \approx 2$ , since the quantities  $\lambda_1$ ,  $\lambda_2$ , and  $\lambda_3$  are approximately equal, and  $[OH + H_2O_2] \approx [H]$ .<sup>[13]</sup> Then for  $T = 273^\circ\text{K}$  the value  $B/B_0 \equiv B/B_C \approx 0.4$  will correspond to  $B\lambda_0/B_0\lambda \approx 0.8$ , thus favoring the solution with  $\Delta t_{\nu}$ , i.e., the observed temperature dependence of the residual polarization of the muon is determined by the competition of the chemical reactions with the depolarization due to the hyperfine interaction.

Within the framework of the developed depolarization model, the accuracy with which the average time of entry of the mesic atom into the chemical reaction at a given temperature is determined by the corridor between the solid and dashed curves on the figure in the region  $\lambda_0 \approx \nu$  ( $\pm 15\%$ ) and by the statistical errors of the experiment, which can be taken into account by shifting the experimental points in the direction of the  $\lambda_0$  axis within the limits of these errors. Thus the average  $\bar{t}_1 = (2.5 \pm 0.4) \times 10^{-12}$  sec for  $T = 273^\circ\text{K}$  and  $\bar{t}_1 = (8.3 \pm 1.2) \times 10^{-12}$  sec for  $T = 80^\circ\text{K}$ .

It should be noted that the experimentally observed temperature dependence is described by the section of the curve having the maximum slope. This allows us to state that the contribution of the hot reactions of the mesic nitrogen is small, for otherwise the slope of the plot of the residual polarization would be smaller. Consequently, the cooling of the hot zone at the location of the "Coulomb explosion" occurs within a time shorter than  $10^{-12}$  sec, which is in qualitative agreement with<sup>[19]</sup>. The decrease of the value of the residual polarization in water with increasing temperature above  $T = 273^\circ\text{K}$ <sup>[2]</sup> can be connected with the change (disordering) of the structure of the water and with the increase of the diffusion rate of the radicals, leading to a decrease in their concentration in the region of the "Coulomb explosion."

The foregoing considerations can apparently be employed for a qualitative explanation of the differences between the residual polarizations in hydrocarbons.<sup>[2]</sup> The decrease in this quantity on going from cyclic compounds to aromatic ones may be due to the decrease in the concentration of the radicals near the mesic radical, as a result of migration of the energy from the zone of the "Coulomb explosion." As is well known, the best conditions for this purpose are realized precisely in the aromatic compounds. We can similarly explain also the decrease of the residual polarization on going from styrene (monomer) to polystyrene (polymer).

One should apparently expect the "Coulomb explosion" and the accompanying formation of the zone of free radicals to play a decisive role in the explanation of the depolarization of negative muons in other condensed substances having a complicated molecular structure.

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