ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ

A.E. Ignatenko

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# DEPOLARIZATION PROCESSES OF NEGATIVE MUONS

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## Abstract

On the basis of measurements of the asymmetry of ( $\mu$-$e$ ) - decay electrons the depolarization processes of negative muons in different matters have been studied with scintillation counters. It has been found out that most essential muon depolarization takes place after their slowing down in mesic atom production. It has benn shown that reasons causing muon depolarization in a mesic atom are the following: a) spin-orbital interaction leading to the fine structure of energy levels, b) interaction of muon and nuclear magnetic moments responsible for mesic atom hyperfine structure, c) muon interaction with quadrupole nuclear distortion, d) interaction of muon magnetic moment with the magnetic field of the electron shell. The principal peculiarities of each depolarization process are described.

## I. Introduction

Mesons are of special importance among elementary particles known at present. Though in many cases they remind electrons and positrons still they differ considerably by their mass and lifetime. From the point of view of the field theory such difference might be a consequence in muon and electron interactions with other elementary particles. However, this difference has not been found out yet. In this connection the study of muon interaction with other particles, as for example, interaction between fermion pairs (proton, neutron), (muon, neutrino) is of great interest. The discovery of parity non-conservation in weak interactions provides a number of possibilities for the experimental investigation of interactions of this kind. Thus, in some papers it was suggested that the asymmetry of products of reactions attending nuclear absorption of polarized muons should be studied. Muon interaction with nuclei greatly depends on the state in which it is. This state, in its turn, depends on the processes which take place for polarized muons in matter before they are captured by the nucleus. Therefore, the investigation of muon depolarization in different matters is of considerable interest.

## 2. Theory

Negative muon depolarization in matter can be devided into two stages: depolarization taking place during their slowing down and depolarization taking place in mesic atom production. From [1-4] it follows that depolarization due to muon scattering on unpolarized electrons and in the Coulomb nuclear field does not occur. In [5-7] it is shown that depolarization of slowed down muons cannot take place also due to the interaction of their magnetic moment with magnetic fields being present in matter. The most considerable depolarization will take place after slowing down in mesic atom production. Reasons responsible for depolarization are the following: a) spin-orbital interaction causing fine structure of mesic atom energy levels. b) interaction of muon and nuclear magnetic moments which is responsible for mesic atom hyperfine structure, c) muon interaction with quadrupole nuclear distortion and d)interaction of muon magnetic moment with the magnetic field of the electron shell.

Let us consider these mechanisms separately.

## a) Mechanism of Spin-Orbital Interaction

In cascade transitions to the ground state a mesic atom undergoes a lot of intermediate states. For lower levels the inequality:

$$\Delta_{n\ell} \gg \Gamma_{n\ell} \tag{1}$$

takes place, where $\Delta_{n\ell}$ is distance between the levels of hyperfine structure with the quantum numbers $n$ and $\ell$ but with different j = 1 + 1/2, whereas $\Gamma_{n\ell}$ is the corresponding level width which is equal to the sum of radiation width and the width with respect to Auger transitions. Physically inequality (I) means that the time of muon staying at a given level is considerably longer than the time of muon spin reorientiation in the magnetic field produced by its orbital movement. The average value of the degree of muon polarization on K-orbit of mesic atoms is calculated in papers/8-10/. The idea of calculations is as follows. One considers a muon with spin projection to the axis $z$ $S_z^0$. At the moment t = 0 the muon is captured by the Coulomb nuclear field into the shell which characterizes $n$ and $\ell$. Since at the initial moment only spin muon state is determined, then with t = 0 the muon state at the shell ( $n, \ell$ ) is given by the set (2 $\ell$ + 1) of the wave functions

$$\Phi_0(0) = R_{n\ell}(r) Y_{\ell\ell_z^0}(\vec{r}/r) \chi_{ss_z^0} \tag{2}$$

where $R_{n\ell} Y_{\ell\ell_z^0}$ is the normalized wave function of a mesic atom (spin being not taken into account) and the projection of the orbital moment $\ell_z^0$ can have values $\ell_z^0 = -\ell, -\ell+1, \dots +$ $\dots + \ell$ with an equal probability $P_{\ell_z^0} = \frac{1}{2\ell+1}$. When spin is taken into account, the muon state in a mesic atom, without $n$ and $\ell$, is also characterized by the the value of its total moment j = 1 + I/2 and by the value of the projection to the axis $z$ of the total moment $j_z$. Consequently, the wave function of the steady state will be of the form:

$$\Psi_{n\ell jj_z}(t) = R_{n\ell j}(r) \Omega_{j\ell j_z}(\vec{r}/r) e^{-\frac{i}{\hbar} E_{n\ell j} t}$$

where $\Omega_{\ell j j_z} = \sum_{\ell_z s_z} C^{jj_z}_{\ell\ell_z s s_z} Y_{\ell\ell_z}(\vec{r}/r) \chi_{ss_z}$ is global spinor, $C^{jj_z}_{\ell\ell_z ss_z}$ the Clebsch-Gordan coefficient and $E_{n\ell j}$ is the energy of muon coupling in the subshell ( $n\ell j$ ) of a mesic atom. It is worthy of notice that initial wave function (2) is not one of the functions of form (3) which are taken at the moment t=0, and is the following superposition of two steady state solutions with the data $n$ and $\ell$ and $j=\ell\pm\frac{1}{2}$:

$$\Psi(0)=\sum_j C^{jj_z^0}_{\ell\ell_z^0 s s_z^0}\,\Psi_{n\ell j j_z}(0)\quad,\quad j_z^0=\ell_z^0+s_z^0$$

Evidently, at the moment $t>0$ the muon wave function which had form (2) with $t=0$, will be

$$\Phi(t)=\sum_j C^{jj_z^0}_{\ell\ell_z^0 s s_z^0}\,\Psi_{n\ell j j_z^0}(t) \tag{4}$$

If condition (I) is carried out, the states with $j=\ell+\frac{1}{2}$ and $j=\ell-\frac{1}{2}$ can be considered independently. Then from (4) for the probability $P_j$ of the muon being in the state $(n,\ell,j)$ with the given $j$, it is easy to obtain the expression:

$$P_j=\frac{1}{2\ell+1}\sum_{\ell_z^0}\left(C^{jj_z^0}_{\ell\ell_z^0 s s_z^0}\right)^2=\frac{2j+1}{2(2\ell+1)} \tag{5}$$

On the other hand, the average value of the operator $\sigma_z$ for the muon in the state with the given $n,\ell$ and $j$, being equal to the degree of its polarization in this state, is given by the relations:

$$\langle\sigma_z\rangle_{n\ell j}=\frac{\left[\frac{3}{4}+j(j+1)-\ell(\ell+1)\right]^2}{3j(j+1)}=\begin{cases}\frac{2\ell+3}{3(2\ell+1)}\,(2S_z^0) & \text{with } j=\ell+\frac{1}{2}\\ \frac{2\ell-1}{3(2\ell+1)}\,(2S_z^0) & \text{with } j=\ell-\frac{1}{2}\end{cases} \tag{6}$$

Since muons appear to be captured originally into states with considerably large $\ell$ /II/, one can obtain from (4) and (5).

$$P_j\approx\frac{1}{2}\quad\text{and}\quad\langle\sigma_z\rangle_{n\ell j}\approx\frac{1}{3}(2S_z^0) \tag{7}$$

From the point of view of physics it means that mesons being captured into greatly excited mesic atom shells with approximately equal probability pass over to the state with $j=\ell+\frac{1}{2}$ and $j=\ell-\frac{1}{2}$ conserving about I/3 of its initial polarization. Under the assumption that muon transitions into the ground state of mesic atoms take place due to dipole radiation and Auger-transitions, in /8/ it is shown that from the state (n, $\ell$, j = 1 + 1/2) muons reach K-shell conserving their polarization equal to 1/3 of the initial one, whereas from the state (n. $\ell$ , j = 1-1/2) they reach K-shell completely depolarized. Thus, if at the initial moment a oompletely polarized muon is captured into the mesic atom shell (n, $\ell$), the degree of muon polarization at K-orbit of the mesic atom is 17% according to /8-9/ and 50% according to /10/ . It should be stressed that from all the abovementioned the knowledge of the probability of meson "arrival" to different shells (n, $\ell$ ) at the initial moment and the knowledge of ways of meson transitions from excited states to the initial ones are very important. However, reliable informations concerning them are absent at present.

## b) Mechanism of Hyperfine Structure Caused by Spin Coupling of the Muon and the Nucleus

This mechanism will influence upon muon polarization in the ground and excited states of a mesic atom. It can be easily proved if one compares the time $t'$ of meson presence at lower levels with the time $t$ of muon spin reorientation in the nuclear field. According to the estimates made in /10,12-15/ the value $t$ is considerably less than $t'$ .

Let us explain the matter by an example when nuolear spin I = I/2 and at the initial moment a polarized meson with the projection of the spin to the axis $z$ , equal to I/2 comes to K-orbit of a mesio atom. Owing to hyperfine structure interaction the mesic atom of the oase under study can be in states with total spins F = 1 and F = 0. If the nucleus was not polarized, the sum of projections to the axis $z$ of nuclear and meson spin states have the values $I_z + S_z = 1$ and $I_z + S_z = 0$ with equal probability. In the first case the spin state of the system (a muon + a nucleus) is given at t=0 by the function $\Phi_1(0) = \chi_{\frac{1}{2}} \cdot \chi_{\frac{1}{2}}$ , and in the second case by $\Phi_0(0) = \chi_{\frac{1}{2}} \cdot \chi_{-\frac{1}{2}}$ (where the first spinor relates to muon spin, while the second - to nuolear spin). Evidently at the moment $t>0$ the wave functions will be of the form:

$$\Phi_1(t) = \chi_{\frac{1}{2}} \cdot \chi_{\frac{1}{2}}\, e^{-\frac{i}{\hbar}E_1 t} , \quad \text{and}$$
$$\Phi_0(t) = \frac{1}{2}\left\{(\chi_{\frac{1}{2}} \cdot \chi_{-\frac{1}{2}} + \chi_{-\frac{1}{2}}\chi_{\frac{1}{2}})\, e^{-\frac{i}{\hbar}E_1 t} + (\chi_{\frac{1}{2}}\chi_{\frac{1}{2}} - \chi_{-\frac{1}{2}} \cdot \chi_{\frac{1}{2}})\, e^{-\frac{i}{\hbar}E_0 t}\right\}$$

respeotively, where $E_1$ and $E_0$ are energies of mesic atom coupling at states with F = 1 and F=0.

Thus in the oase with the initial oondition $\Phi_1(0)$ the wave function is an eigen function of the mesic atom with an account of hyperfine struoture for the states F=1, $F_z$=I.

and in the case of the initial condition $\Phi_0^I(0)$ it is a suprposition of states with F = I, $F_z$= 0 and F = 0. States with F =1 and F = 0 are incoherent /12/. Taking into consideration that at states F = 1, $F_z$ = I and F =0 a muon is completely depolarized and at states F = I, $F_z$ = I in conserves its polarization, we draw a conclusion that at K - orbit of the mesic atom muons conserve only 50% of their initial polarization. In a general case when nuclear spin $I \geq \frac{1}{2}$ , the probability for a muon together with a nucleus to form a system with the total spin $F = I \pm \frac{1}{2}$ and its projection $M_F$ is /14/

$$N_+(M_F) = \frac{I + M_F + \frac{1}{2}}{(2I+1)^2}, \qquad N_-(M_F) = \frac{I - M_F + \frac{1}{2}}{(2I+1)^2}$$

Normalization is chosen so that

$$N_+ = \sum_{M_F} N_+(M_F) = \frac{I+1}{2I+1}$$

$$N_- = \sum_{M_F} N_-(M_F) = \frac{I}{2I+1}$$

$$N_+ + N_- = 1.$$

(The sign $\pm$ corresponds to F = I $\pm$ I/2). Muon polarization in these states is

$$\langle \sigma_{z\mu} \rangle_+ = \frac{2I+3}{3(2I+1)}, \quad \langle \sigma_{z\mu} \rangle_- = \frac{2I-1}{3(2I+1)}$$

and on averaging

$$\langle \sigma_{z\mu} \rangle = N_+ \langle \sigma_{z\mu} \rangle_+ + N_- \langle \sigma_{z\mu} \rangle_- = \frac{1}{3} \left[ 1 + \frac{2}{(2I+1)^2} \right] \qquad (8)$$

From this equation it is seen that the value of muon polarization depends upon nuclear spin. E.g., for nuclei with $I = \frac{1}{2}$ polarization should decrease twice; for nuclei with $I \gg 1$ -three times. The detailed account of depolarization in mesic atom excited states was performed in /10/ for the case when I = I/2. Thus, the complete decrease of polarization due to hyperfine structure interaction in the ground states should take place three times. It should be pointed out that each state of hyperfine structure is characterized by its value $g$ -gyromagnetic ratio /14/.

$$g_+ = \frac{1}{I + \frac{1}{2}} (\mu_\mu + \mu_N) \qquad (9)$$

$$g_- = -\frac{1}{I + \frac{1}{2}} \left( \mu_\mu - \frac{I+1}{I} \mu_N \right) \qquad (10)$$

where $\mu_\mu$ and $\mu_N$ are meson and nuclear magnetic moments, respectively. All the abovesaid refers, evidently, to the case with isolated mesic atoms. The presence of medium can complicate the phenomenon, e.g., it may lead to the appearence of muon transitions between the levels of hyperfine structure. Thus, in metals two kinds of transitions are possible which are accompained either by the conservation of conductivity electrons or by magnetic dipole radiation[16]. In liquid hydrogen mu-meson jumping from one proton to another with simultaneous transition to the lower state of hyperfine structure is possible[17].

### c) Mechanism of Depolarization Due to Muon Interaction with Nuclear Distortion

This mechanism has been considered in [18] for even-even nuclei. The diagonalization of the Hamiltonian of the meson-nucleus system $H = H_0 + H_R + H_q$ (here $H_0$ is the muon Hamiltonian in the monopole nuclear field, $H_R$ is the operator of rotation nuclear energy and $H_q$ is the operator of quadrupole muon interaction with the nucleus) shows that quadrupole interaction changes considerably the eigen functions of the system, which correspond to the muon only in 2p-state[19]. In this approximation the polarization od P muon in IS - state can be written as

$$P = A_q W_{1/2} \langle \sigma_{2p_{1/2}} \rangle_0 + B_q W_{3/2} \langle \sigma_{2p_{3/2}} \rangle_0 ,$$

where $W_{1/2}$ and $W_{3/2}$ are probabilities of muon transitions through 2PI/2 and 2P3/2 - states, respectively; $\langle \sigma_{2p_{1/2}} \rangle$ and $\langle \sigma_{2p_{3/2}} \rangle$ is muon polarization in these states in the absence of quadrupole interaction; $A_q$ and $B_q$ are factors taking into account depolarization caused by the above-said disadvantage. In muon cascade transition to IS - state there is a probability that the nucleus remains with the first excited rotation level[19], the lifetime of which $\sim 10^{-9}$ sec is adequate for muon spin reorientation in IS - state due to hyperfine disintegration of IS-level. The factor determining the depolarization $D_q$ caused by this effect is $D_q = 1 - \frac{2}{3} W_e$ where $W_e$ is the probability of excitation of the first rotation nuclear level.

In considering[18] muon transitions from upper levels to IS - state through states described by the eigen functions of the Hamiltonian $H$, it was found that $P \simeq \simeq \frac{1}{6} B_q D_q$. The obtained values $B_q$ and $D_q$ and the values of magnitudes which determine them ($E_{fs}$ is the fine structure disintegration of the 2p-level, $E_R$ is the energy of the first rotation nuclear level and $E_q = \langle 2P | H_q | 2P \rangle$ are enlisted in Table I.

TABLE

| Element | $E_{\beta}$(kev) | $E_R$(kev) | $E_q$(kev) | $B_q$ | $\mathcal{D}_q$ |
|---|---|---|---|---|---|
| $Gd^{158}$ | 91.5 | 79 | 52 | 0.63 | 0.61 |
| $W^{184}$ | 137 | 112 | 43 | 0.64 | 0.64 |
| $Th^{232}$ | 216 | 52 | 83 | 0.38 | 0.6 |
| $U^{238}$ | 226 | 44 | 91 | 0.38 | 0.59 |

As it follows from the Table, muon interaction with nuclear distortation can lead to considerable muon depolarization.

### d) Mechanism of Hyperfine Structure Caused by Muon and Electron Shell Spin Coupling

Mesic atom production is concerned with the destroy of the electron shell of the initial atom. The matter is that in muon cascade transitions the excitation of and ionization of atoms are possible. After mesic atom production the electrons of the shell find themselves in the nuclear field with the new effective charge $Z-1$. This circumstance also can lead to shell ionization. The lifetime $t_0$ of the shell excited state for free mesic atoms depends only upon electron cinfiguration and the degree of excitation.

When mesic atoms are produced in medium, the time $t_0$ depends considerably on the nature of medium atom coupling. If a mesic atom is in metal, the electron shell returns to its ground state in a very short time (less than in $10^{-12}$ sec.) compared to the muon lifetime $\tau$. On the other hand, in ion crystals or dielectrics the time $t_0 > \tau$. Consequently, at the moment of mesic atom decay the electron shell state depends upon the kind of a compound to which the atom under investigation belongs and upon the aggregate state of matter. The electron shell can influence upon muon polarization only in the ground state[23]. It can be easily proved if one compares the time $t'$ of muon staying at lower levels with the time $t$ of muon spin reorientation in the shell field. Taking into account that in the first approximation the energy of hyperfine interaction in mesic atoms is of the same order as in the muonium,

$$\Delta W = -\frac{32 \mu_N \cdot P_{eff}}{3 a_{e\mu}^3}$$

(where $\mu_\mu$ is muon magnetic moment, $\mu_{eff}$ is the effective magnetic moment of the electron shell, $a_{e\mu}$ is the Bohr radius) one can easily see that the inequality $t \ll t'$ is justifiable only for the IS - level.

When an isolated mesic atom with zero nuclear spin has electron shell moment, paramagnetic moment consists of three times:

I) muon magnetic moment $\mu_\mu = \frac{\sqrt{3}\,\mu_B}{207}$

2) electron orbital moment $\mu_L = \mu_B \sqrt{L(L+1)}$

3) electron spin moment $\mu_S = 2\mu_B \sqrt{S(S+1)}$

When mesic atoms are produced in medium, their paramagnetism will be subjected to the influence of neighbouring atoms. And the compensation of either these or those moments will be a consequence of it. Everything depends upon the fact, electrons of what shells create magnetic moment. By analogy with the properties og of ion magnetic moments of paramagnetic matters one may expect that if mesic atoms are formed either of lanthanide or actinide atoms. where magnetic moment is caused by electrons situated deeply in the atom and which are least of all subjected to external influence, paramagnetism of such mesic atoms in medium will be caused by the moments $\mu_L$, $\mu_S$ and $\mu_\mu$ . In the case of atoms of transition elements, where atomic magnetic moment is caused by electrons which are situated not deeply in the atom and which are most of all subjected to external influence, mesic atoms in media can have only spin moments $\mu_S$ and $\mu_\mu$ . And at last mesic atoms of diamagnetic matters or of weak-paramagnetic normal metals in media can have only the moments $\mu_\mu$

It should be stressed that in matters with $\mu_{eff} \neq 0$ mesic atoms will be created in two states of hyperfine structure with $F = J_e \pm \frac{1}{2}$ . Hyperfine disintegration in the ground mesic atom state is considerably greater y than $\frac{\hbar}{\tau}$ . Therefore, states with $F = J_e + \frac{1}{2}$ and $F = J_e - \frac{1}{2}$ for an isolated mesic atom form an incoherent mixture. Consideration which is analogous to that made for mechanism b) shows that the degree of muon polarization $P$ which is at K-orbit averaged over two states of hyperfine structure, is

$$P = \frac{1}{3} P_0 \left[ 1 + \frac{2}{(2J_e+1)^2} \right] \qquad (12)$$

where $J_e$ is the angular momentum of the electron shell, $P_0$ is the degree of muon polarization at the initial moment of its "arriving" at K - shell.

### 3. Experiment

At the existing muon beam intensities of accelerators the experimental test of theory predictions is possible only in the production of mesic atoms in condensed matter. The presence of medium may complicate the phenomenon. Choosing matters for investigation one should take into consideration that matters consisting of atoms of the same kind or hydrogenious matters are of practical interest. The matter is that the utilization of matters consisting of atoms of different kinds leads to additional difficulties in the interpretation of experiments due to the lack of knowledge on the probability of mesic atom production in various components. As for hydrogeneous matters, one may hope that here hydrogen does not play any important role in the production of mesic atoms. Matters should be chosen so that there was a possibility of clearing up the features of each depolarization mechanism. This can be achieved if one uses the following matters as objects for investigation:

I) dielectrics (liquid hydrogen, paraffin, plythene, water, sulfur and phosphorus);

2) diamagnetic and weak-paramagnetic normal metals (graphite, magnesium, aluminium, zn: zinc, cadmium and lead);

3) paramagnetic transition metals (chromium, molybdenum, palladium and tungsten).

Indeed in mesic atom production of matters (groups I and 2 which have 85-95% atoms with zero nuclear spin, one may expect that muons will be depolarized only due to mechanism a). If mesic atoms are foemed in metals of group 3) containing internal d-electrons in atoms with zero nuclear spin states, muon depolarization will take place due to mechanisms a) and d), whereas in mesic atoms with nuclear distortion (tungsten) it will take place due to mechanism c) also. And at last, when using the matters of groups I) and 2) atoms if which have nuclear spin states differing from zero, we can have basic depolarization mechanisms a) and b).

Muon polarization in these matters has been investigated in papers[20-23] by measuring anistropy in the electron angular distribution of the decay $1+a\cos\theta$ by a precession method[24]. Anistropy was measured as follows. For those matters of group I) where the basic mechanism of depolarization should be mechanism a) the electronic system was set to register the frequency of the spin precession of a free meson. In experiments with matters of groups I) and 2) having nuclear spin states differing from zero,. the electronic system was set to register the frequency of mesic atom spin precession calculated on the basis of formulae (9) and (10). As for the existence of mechanism d) in matters of group 3), the problem is more complicated. The explanation of this problem can be obtained basing on the measurement of the asymmetry of (mu-e)-decay electrons by the following two methods. In the first method the electronic system is set to register the frequenoy of spin precession of a free muon. As it follows from formulae (9) and (10) , in the given magnetic field $H$ the frequency of the spin precession of mesic atoms having the electron moment and the meson moment, is several orders higher than the frequency of the spin precession of a free muon. Owing to a great difference in frequencies one can consider the nature of mesic atom paramagnetism basing on the number of el electrons $N_{max}$ and $N_{min}$ with two values of the intensity of the magnetic field (in which the target is located) which corresponds to calculated by the formula:

$$t_1 + \Delta t = \frac{T}{2} = \frac{\pi mc}{eH}$$

where $t_1$ is delay time, $\Delta t$ is gate "width" and $T$ is precession period. Indeed, for mesic atoms having the electron moment, the value of the ratio $\xi = \frac{N_{max}}{N_{min}}$ will be equal to a unit; mesic atoms whose paramagnetism is caused only by muon spin will have the value $\xi$ differing from a unit. With such a method of investigation the measurement of the value $\xi$ in hydrides of paramagnetic metals having such concentration of hydrogen when the paramagnetism of a compound vanishes to zero, as e.g. $PdH_{0.6}$ might serve as a test experiment directly confirming the existence of electron paramegnetism. Really, the atoms of palladium, being in the solution $PdH_{0.6}$, have no magnetic moment whereas hydrogen does not take part in mesic atom production. The second method of investigating paramagnetism is the measurement of electron asymmetry in the case when the electronic system is set to register the frequency of mesic atom spin precession calculated by formulae (9) and (10). However, this kind of experiments is more complicated. Indeed, the difference from a unit of the value $\xi$ observed experimentally in the case when mesio atoms have electron moment, as is seen from equation (12), is considerably less. Besides, the existence of two states of hyperfine structure and also the presence of transitions between them (for example, from F =I to F =0) will complicate the interpretation of experiments. Paper/23/ presents the description of investigation performed by the first method.

The values $a_0$ asymmetry coefficients for the whole integral spectrum, and the va -

lues $\xi = \frac{N_{max}}{N_{min}}$ are enlisted in Table II. They were obtained for the above-quoted matters in /20-23/. Corrections which take into account time delay, "gate" width, muon decay and the solid angle of an electron detector are included in the given values $a_0$ and $\xi$. The indicated errors are standard statistical deviations.

T A B L E II

| Matter | | Nuclear spin | $-a_0$ | $\xi = \frac{N_{max}}{N_{min}}$ |
|---|---|---|---|---|
| 1. Liquid hydrogen | Dielectrics | I/2 | 0.005±0.005 | |
| 2. Polythene | Dielectrics | 0 | | 1.10±0.2 |
| 3. Paraffin | Dielectrics | 0 | | 1.09±0.02 |
| 4. Water | Dielectrics | 0 | 0.043±0.005 | |
| 5. Sulfur | Dielectrics | 0 | 0.042±0.006 | |
| 6. Phosphorus (red) | Dielectrics | I/2 | 0.025±0.005 | |
| 7. Graphite | | 0 | 0.045±0.005 | I.I0±0.02 |
| 8. Magnesium | Diamagnetic and weak-paramagnetic normal metals | 0 | 0.058±0.008 | |
| 9. Zinc | Diamagnetic and weak-paramagnetic normal metals | 0 | 0.056±0.0II | |
| 10. Cadmium | Diamagnetic and weak-paramagnetic normal metals | 0 | 0.055±0.012 | |
| 11. Lead | Diamagnetic and weak-paramagnetic normal metals | 0 | 0.054±0.013 | |
| 12. Palladium hydride ($PdH_{0,6}$) | | 0 | | I.09±0.02 |
| 13. Aluminium | | 5/2 | 0.007±0.007 | |
| 14. Chromium | Paramagnetic transition metals | 0 | | I.00±0.02 |
| 15. Molybdenum | Paramagnetic transition metals | 0 | | 0.99±0.02 |
| 16. Palladium | Paramagnetic transition metals | 0 | | I.00±0.02 |
| 17. Tungsten | Paramagnetic transition metals | 0 | | 0.99±0.02 |

## 4. Comparison of the Theory with the Experiment

Knowing the values $a_0$ and $\xi$, one may determine the degree of negative muon depolarization, e.g., by comparing with the asymmetry observed in $\mu^+$-meson decay and by assuming that mu-decay should be invariant with respect to combined transformation of the inversion of spatial coordinates and charge conjugation. In carrying out this requirement one can easily prove that the relation:

$$\frac{a_-}{P_-} = \frac{a_+}{P_+}$$

takes place, where $\rho_+$ and $\rho_-$ are polarization degrees, and are asymmetry coefficients in the integrated over positron (electron) energy angular distributions $1 + a_\pm \cos\theta$, for mu⁺ and mu⁻ - mesons, respectively. From relation (13) it follows that by comparing the values $a_o$ and $\xi$ one may compare polarization degrees. As it follows from Table II, the values $a_o$ and $\xi$ for graphite, paraffin, polythene, water, magnesium, sulfur, zinc, cadmium and lead are obtained to be equal within statistical errors. The degree of polarization obtained from the values $a_o$ and $\xi$ reaches the value of the order of 17%. The independence of the values $a_o$ and $\xi$ for $Z \geq 6$ upon $Z$ and also their absolute values are in good agreement with theoretical calculations /8,9/ which take into account only mechanism a) and do not agree with analogous calculations /10/. These facts and also coincidence of the precession frequencies of mesic atom spin and "free muon" spin show that depolarization mechanism d) is absent. To understand this, let us consider first the case when mesic atoms are produced in metals. Metals including graphite also may be considered in the first approximation as an assembly of ions submerged into electron gas. If a metal belongs to group 2), its ions are deprived of magnetic moment. Therefore, evidently, in mesic atom production due to the fact y that the lifetime $t_o$ of the excited electron shell state is considerably less than the time $t'$ of muon spin reorientation in the shell magnetic field, the ion electron state, in the end, is not destroyed while atomic ionization is accompanied only by the emission of collectivized conductivity electrons. The equality of the values $\xi$ for these metals and palladium hydride $PdH_{0.6}^{0.6}$ proves that in mesic atom production of the above-said metals (group 2) electron paramagnetism does not arise.

The process of mesic atom production in dielectrics, where $t_o \gg t'$, is quite different. Mesic atoms of carbon in paraffin and polythene and also of oxigen in water and sulfur can have no depolarization mechanism d) due to two reasons. Firstly, it may occur if mesic atoms are negative ions having the electron configuration of initial atoms. Secondly, it is possible that mesic atom production is concerned with the destroy of the electron shell of initial atoms. Then, according to /9/ the electron moment will be absent if there is its complete compensation under the influence i of neighbouring atoms. Only further investigations can help to explain which of these two subpositions is correct.

The results of experiments with palladium and palladium hydrine $PdH_{0.6}$ directly show that in palladium muon depolarization takes place due to mechanisms a) and d). Indeed, ions of this transition metal have magnetic moment caused by the electrons of internal magnetic active 4d - shells. In the compound $PdH_{0.6}$, as is shown by the equality of measured values $\xi$ for graphite, polythene and paraffin, the influence of hydrogen on the depolarization process is not felt.

The equality to a unit of the values $\xi$ for chromium and molybdenum transition metals of group 3), and also their coincidence with each other can be in two cases:

I) if there is complete meson depolarization in those matters and

2) if mesic atom paramagnetism is caused by the magnetic moments of the electron shell and the muon.

In the case with these metals a test experiment, directly confirming the presence of electron paramagnetism analogous to the experiment with palladium cannot be performed, unfortunately. The reason of it is that when hydrogen is dissolved in these metals, no hydrides are formed. It is difficult to imagine that the metals - chromium and molybdenum could greatly differ from the above mentioned matters of groups I) and 2), as far as the process of muon depolarization is concerned. Indeed, as is known, the probability of mesic atom production is equal to a unit. Cr and Mo consist also of 80-90% of atoms with zero nuclear spins. The nuclei of these atoms have no special properties which could cause complete muon depolarization. Consequently, the existence of other depolarization mechanisms in mesic atoms with such $Z$ except mechanism a) is hardly probable. The only fact by which Cr and Mo differ from the above-quoted matters is that their atoms have unclosed internal shells. Therefore, the results of experiments with Pd and $PdH_{0.6}$ show with great probability that in the case with c Cr and Mo, whose ions have magnetic moment differing from zero and which is caused by the electrons of 3d- and 4d-shells, respectively, we have depolarization mechanism d).

The results of experiments with tungsten deserve special attention since contrary to Pd, Cr and Mo, tungsten has mesic atoms with nuclear distortion. If the supposition on the binding of the observed muon "depolarization" with quadrupole nuclear distortion is correct, then according to theoretical assumptions[18] there should be the following relation between the values $a_0$ for carbon and tungsten: $(a_0)_W = 0.4(a_0)_C$. Precession frequency in the magnetic field of tungsten mesic atom spin should coincide with the precession frequency of "free" muon spin. Using the normal law of error distribution, one can show that the case $\xi_{\text{theoret.}} = \xi_{\text{measur.}}$ is not acceptable since $\xi_{\text{measur.}} < \xi_{\text{theoret.}}$ with a 70% probability. This circumstance proves that the observed experimentally "complete" muon depolarization is difficult to explain only by muon interaction with nuclear distortion. The results of experiments for Pd, Cr and Mo show with great probability that in the case with tungsten we deal along with depolarization mechanisms a) and c) with mechanism d). It should be noted that despite the fact that the atoms of tungsten have magnetic moment of very small efficiency, it can become apparent in these experiments due to a considerable sensitivity of the investigation method. Indeed, muons have magnetic moment an order higher than that of the nuclear magneton, the time of muon spin reorientation in the field of the mesic atom shell ($10^{-10}$ sec.) being several orders less than its lifetime. Evidently, in order that the above-mentioned conclusions should be more definite it is necessary also to observe directly the spin precession curves of mesic atoms Cr, Mo and W.

Consider now the results of experiments for matters atoms of which have nuclear spin states differing from zero.

In experiments with phosphorus we observed the precession of mesic atoms mesic nuclei of which (the meson-nucleus system) is in the state F=I[24]. This fact directly proves that in such mesic atoms there is mechanism b) along with depolarization mechanism d).

In experiments with liquid hydrogen[20] and aluminium[22] no dependence of the counting rate of electrons on the current of a magnetizing coil was observed. Since the precession curve, observed in experiments with aluminium, is a result of the superposition of muon precession curves, being in the states of hyperfine structure F = 3 and F =2, the obtained curve could not be interpreted. Compare now the measured values with those predicted theoretically.

Basing on the statemants mentioned at the beginning of this section, one may expect that in such matters as liquid hydrogen, phosphorus and aluminium the influence of the atomic electron shell on meson depolarization will be absent. In the absence of mechanism d) according to the theoretical predictions[13-15] there should be the following relations between the values $a_0$ for carbon, phosphorus, aluminium and hydrogen:

$$a_H = a_P = \frac{1}{2} a_C \quad \text{and} \quad a_{Al} = \frac{1}{3} a_C$$

according to predictions[10] $a_H = a_P = \frac{1}{3} a_C$ . Applying the normal law of error distribution, we can show that the case $a_H = a_P$ is forbidden since $a_H < a_P$ with a 99% probability. The case $a_{Al} = \frac{1}{3} a_C$ does not contradict the experiment but according to experimental data, the probability that $a_{Al} > \frac{1}{2} a_C$ is equal to 5% whereas the probability that $a_{Al} < \frac{1}{3} a_C$ is 39%. The values of the ratios $\frac{a_C}{a_P}$ were analysed by the criterion $\chi^2$ . The limits of this ratio having a I% probability (figures without brackets) and 5% (figures within brackets) are obtained to be the following:

I.2 (1.4) ÷ (13.0) 3.7 for the case $a_p = \frac{1}{2} a_c$

0.6 (0.7) ÷ (1.5) 1.8 for the case $a_p = a_c$

As is seen, the experimental value $\frac{a_c}{a_p} = 1.8$ is well consistent with the value expected theoretically in the case $a_p = \frac{1}{2} a_c$ , and is outside one per cent limits for the case $a_p = a_c$ .

Making use of the fact that the relation $a_p = a_c$ contradicts the experiment while the relations $a_p = \frac{1}{2} a_c$ and $a_{p\ell} = \frac{1}{3} a_c$ do not contradict experimental data, we may say that the results of measurements do not contradict theoretical predictions /13-15/ but do contrudict the results of paper /10/. This circumstance shows also that when red phosphorus powder is used as a target, the probability of meson transition from the upper level of hyperfine structure to the lower one is small /16/. Since the experimental value $\frac{a_c}{a_p}$ is outside one per cent limits for the case $a_p = \frac{1}{3} a_c$ , it may be said that the interaction of hyperfine structure for $\mu^-$ - mesons, being in lower excited states of mesic atoms, is evidently unessential compared to interaction at K-orbit.

And, at last, the fact that $a_H < a_p$ shows with a 99% probability that observed experimentally complete negative muon depolarization in liquid hydrogen cannot be explained only by the effect of mechanisms a) and b); so it is necessary to employ an additional mechanism. Complete depolarization mechanism is explained in /17/ where it is shown that the main role is played by neutral mesic atom scattering of hydrogen on a proton $(\mu^- H) + H \rightarrow (\mu^- H) + H$ .In this scattering the transition of a mu$^-$- meson to another proton with a simultaneous transition of a hydrogen mesic atom to the lower state of hyperfine structure takes place with a large effective cross section. Owing to the fact that the probability of these jumpings in liquid hydrogen ($10^9$ sec.$^{-1}$) is three orders higher than the probability of meson decay ($0.5 \cdot 10^6$ sec.$^{-1}$ ) of a mesic proton, mesic protons will completely return to the ground state of hyperfine structure during mu-meson lifetime, and complete depolarization will be result of it.

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R e f e r e n c e s

I. D.Fournet Davis, A.Engler, C.J.Goebel, T.F.Hoang, M.F.Kaplon, J.Klarman, Nuovo Cimento, 6, 310 (1957).

2. A.M.Bincer, Phys.Rev. 107, 1434 (1957).

3. G.W.Ford, C.J.Mullin, Phys.Rev. 108, 477 (1958).

4. И.И.Гольдман, ЖЭТФ, 34, IOI7 (1958).

5. V.W.Hughes, Phys.Rev. 108, 1106 (1958).

6. G.Lynch, J.Orear, S.Rosendorf, Phys.Rev.Lett. 1, 471 (1958).

7. С.А.Али-Заде, И.И.Гуревич, Ю.П.Добрецов, Б.А.Никольский, Л.В.Суркова, ЖЭТФ, 36, 2327 (1959).

8. И.М.Шмушкевич, ЖЭТФ, 36, 645 (1959).

9. В.А.Джарбашян, ЖЭТФ, 35, 307 (1958).

10. M.E.Rose, Depolarization processes for negative mu-mesons. Preprint Oak Ridge Nat.Lab., (1958).

11. M.B.Stearns, M.Stearns, Phys.Rev. 105, 1573 (1957).

12. J.Bernstein, T.D.Lee, C.N.Yang, M.Promakaft, Phys.Rev. 111, 313 (1958).

13. И.М.Шмушкевич, ЖЭТФ, 36, 953 (1959).

14. H.Überall, Phys.Rev. 114, 1640 (1959).

15. И.С.Шапиро, Л.Д.Блохинцев, ЖЭТФ, 37, 760 (1959). Э.И.Долинский, Диссертация НИИЯФ МГУ (1959).

16. H.Primakoff, Rev.Mod.Phys. 31, 809 (1959).

17. С.С.Герштейн, ЖЭТФ, 34, 463 (1959).

18. Д.Ф.Зарецкий, В.М.Новиков, ЖЭТФ, 37, 1824 (1959).

19. L.Wilets, Kong.Danish.Vidensk.Selsk.Mat.2fys.Medd. 29, 3 (1959).

20. А.Е.Игнатенко, Л.Б.Егоров, Б.Халупа, Д.Чултэм, ЖЭТФ, 35, 894 (1958).

21. А.Е.Игнатенко, Л.Б.Егоров, Б.Халупа, Д.Чултэм, ЖЭТФ, 35, II3I (1958).

22. А.Е.Игнатенко, Л.Б.Егоров, Д.Чултэм, ЖЭТФ, 37, I5I7 (1959).

23. Л.Б.Егоров, Г.В.Журавлев, А.Е.Игнатенко, Ли-Сюань-мин, М.Г.Петрашку, Д.Чултэм, ЖЭТФ (в печати).

24. R.Garwin, L.Lederman, M.Wienrich, Phys.Rev. 105, 1415 (1957).