Measurement of helium-3 and deuterium stopping power ratio for negative muons

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The measurement method and results measuring of the stopping power ratio of helium-3 and deuterium atoms for muons slowed down in the D/3He mixture are presented. Measurements were performed at four values of pure 3He gas target densities, \( \varphi_{3He} = 0.0337, 0.0355, 0.0359, 0.0363 \) (normalized to the liquid hydrogen density) and at a density 0.0585 of the D/3He mixture. The experiment was carried out at PSI muon beam \( \mu E4 \) with the momentum \( p_\mu = 34.0 \text{ MeV}/c \). The measured value of the mean stopping ratio \( S_{3He/D} \) is 1.66 ± 0.04. This value can also be interpreted as the value of mean reduced ratio of probabilities for muon capture by helium-3 and deuterium atoms.

PACS numbers: 34.50.Bw, 36.10.-k

Keywords: stopping power, negative muons, muonic atoms, atomic capture, helium-3, deuterium

I. INTRODUCTION

Atomic capture of pions and muons stopped in a mixture of hydrogen and helium isotopes has been a subject matter of quite a lot of experimental \(^1\) and theoretical investigations \(^{11, 10, 12, 13, 14, 15, 16, 17, 18, 19, 20}\). The investigation of this process is important for understanding physics of exotic system and also for studying elementary processes occurring when negatively charged particles stop in a material. To separate two processes – atomic capture and transfer of muons from \( \mu \)-atoms of hydrogen isotopes in the course of their de-excitation to helium nuclei – is practically impossible if x-rays are used, as usually, as diagnostics. What one usual observes experimentally is the result of interference of a few processes accompanying the muon capture by atoms of hydrogen and helium isotopes. Therefore, it is quite a problem to extract unambiguous information on the law of initial capture of muons by atoms of the hydrogen (deuterium)–helium mixture components. The earlier made assumption that the probability for direct muon capture by atoms of the mechanical H2(D2)/M (M is \(^{3,4}\)He, Ar, Ne ...) mixture is proportional to the charge and concentration of each component (Fermi–Teller Z-law \(^{21}\)) turned out to be wrong. Experimental data \(^{17}\) revealed deviation from the Fermi–Teller law. The Z-law is based on the assumption that the atomic capture probability is proportional to muon energy loss on atoms of the mixture components. Actually, there is no simple relation between the stopping power of a particular type of atom and the probability for muon capture by this atom. For the binary mixture He/H it is convenient to express the atomic capture probabilities \( W_{He}, W_H \) by per-atom capture ratio \( A \) (reduced ratio) defined as \( (W_{He}/C_{3He})/(W_H/C_H) \)

\[
W_H = \frac{1}{1 + Ac}, \quad W_{He} = \frac{Ac}{1 + Ac}
\]

where \( c = C_{3He}/C_H \) is the ratio of the helium and hydrogen atomic concentrations.

Recently a series of experiments on the study of \( \mu \)-atomic and \( \mu \)-molecular processes in a D/3He mixture has been carried out at the Paul Scherrer Institute meson factory \(^{22, 23, 24}\). In the experiments we measured the following characteristics: the nuclear fusion rate in a charge-asymmetrical muon complex (\( d\mu^3\)He); the probability for transition of the \( d\mu \) atom from the excited to the ground state (\( q_{\mu} \)); intensities of x-ray radiation of \( \mu \)He atoms resulting both from muon capture by \(^3\)He atoms and from transfer of the muon from the \( d\mu \) atom under its de-excitation to the \(^3\)He nucleus. For correct interpretation of the above-mentioned experimental data it was necessary to have information on the probability for direct capture of muons by deuterium and helium atoms in the D/3He mixture. On the one hand, the value of the capture ratio \( A \) averaged over the data of the papers \(^{11, 12, 13, 14, 16, 17, 18, 19, 20}\) can be used; on the other hand, an attempt may be made to get experimental information on \( S = S_{3He/D} \) as a ratio of stopping powers of helium and deuterium atoms in an independent way from an additional experiment. The description of the method and analysis of the results will be presented in the next section.
the ratio of stopping powers of helium and deuterium per atom is the aim of this work.

II. MEASUREMENT METHOD

In our experiment we used two types of gas targets; one was a D + 5%³He mixture with the density \( \varphi_{\text{mix}} = 0.0585 \) (hereafter all atom number densities \( \varphi \) are normalized to the liquid hydrogen density, \( n_o = 4.25 \cdot 10^{22} \text{ cm}^{-3} \)), the other was a target with pure helium-³. A set of different helium densities \( \varphi_{\text{He}} \) was considered. The deuterium-helium mixture and the helium targets were exposed to the same muon beam in order to keep the same initial energy distributions of muons entering the targets. The momentum of the muonic beam was chosen such as to stop all entering muons inside the D/³He target. In the final stage of the slowing-down muons are captured by the target atoms, form muonic atoms and finally decay via the \( \mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e \) reaction. Decay electrons are then markers of the stopping events. A schematic view of the experimental setup is shown in Fig. 1 (see [22, 25] and the next section for details).

![FIG. 1: Scheme of the experimental setup. E – electron counters, Si – silicon telescopes.](image)

Varying the gas density in the pure helium target we changed the position of the maximum in the muon stopping distribution along the target length. The example of the Monte Carlo simulations presented in Fig. 2 illustrates such a situation. The stopping code [26] with Ziegler parameterization of the stopping powers [27] was used for obtaining the muon stop distributions in the targets. Calculations were performed for the 34.0 MeV/c muon beam. Stopping distributions were calculated for three targets: the D+5%³He mixture with the density \( \varphi_{\text{mix}} = 0.0585 \) (thick solid line), pure ³He with density \( \varphi_{\text{He}} = 0.0380 \) (dashed line) and pure ³He with the density \( \varphi_{\text{He}} = 0.0330 \) (dotted line). Vertical lines show the position of the central (spherical) part of the target; this part is directly seen by the electron counters. The stopping coordinate \( x \) is a distance to the stopping point taken from the entrance position by the beam direction. It is clear, that the number of electrons detected by the electron counters will change when the stopping distribution is shifted.

![FIG. 2: Stopping distributions calculated for three targets with different densities \( \varphi \): D/³He mixture (\( \varphi_{\text{mix}} = 0.0585 \), thick solid line), ³He (\( \varphi_{\text{He}} = 0.0380 \), dotted line), ³He (\( \varphi_{\text{He}} = 0.0330 \), (b)). The beam momentum is 34.0 MeV/c. The energy of incident muons, \( E_{\text{in}} \), is shown in the insert.](image)

The density of the pure helium target can be chosen such that the number of muon stops detected via decay electrons is the same as in the D/³He mixture (we denote this density by \( \varphi_{\text{He}} \)). In such a case spatial distributions of muon stops are equivalent. Such equivalency of the stopping distributions was verified by performing the MC simulations with a set of different ³He densities and examining the differences by \( \chi^2 \)-analysis for both distributions (from D/³He and ³He targets). Figure 3 shows, as an example, the distributions where the minimum of \( \chi^2/\text{df} = 0.92 \) was achieved for pure helium density \( \varphi_{\text{He}} = 0.0342 \). Similar equivalency of the stopping distributions is obtained in the plane perpendicular to the beam axis. The details of the experimental results discussed in the next section also justify the assumption of equivalency of spatial distributions of muon stops for a selected He target density.

From the identity of the spatial distributions in both targets (considering that the initial muon energy distributions are also identical) follows equality of the ranges of stopped muons for any initial muon energy \( E_{\text{in}} \)

\[
\int_{E_{\text{in}}}^{E_{\text{fin}}} \frac{1}{(-\frac{dE_{\text{He}}}{dx})_{\text{He}}} dE = \int_{E_{\text{in}}}^{E_{\text{fin}}} \frac{1}{(-\frac{dE_{\text{mix}}}{dx})_{\text{mix}}} dE. \quad (4)
\]

The above equation can be rewritten in terms of the atomic stopping powers \( s_{\text{He}}, s_D \)

\[
\left( \int_{E_{\text{in}}}^{E_{\text{fin}}} \frac{dE}{s_{\text{He}}} \right)_{\text{He}} = \left( \int_{E_{\text{in}}}^{E_{\text{fin}}} \frac{dE}{s_{\text{mix}}} \right)_{\text{mix}}. \quad (5)
\]
where $S$ is the ratio of stopping powers being the subject of the measurement

$$S = \frac{s_{He}(E)}{s_D(E)}. \quad (6)$$

In appendix A we argue how a simple and more useful formula for the mean ratio of the stopping powers can be derived from relations (4),(5) when the behavior of the individual stopping powers of helium-3 and deuterium is taken into account. Such a formula reads

$$S_{He/D} = \overline{S} = \overline{S(E)} = \frac{\bar{C}_D \varphi_{mix}}{\varphi_{He} \overline{C}_He \varphi_{mix}}, \quad (7)$$

where $\overline{E}$ is the average energy of the initial muon energy distribution. The above formula gives the recipe for measurement of the mean ratio of the helium-3 and deuterium atomic stopping powers.

The specific density $\varphi_{He}$ (needed for obtaining $S$ by formula (7)) is experimentally established by measuring the yields of electrons from muon decays in the D/3He mixture target and in a set of pure 3He targets.

### III. Measurement and Results

The experiment was carried out at muon channel $\mu$E4 at the Paul Scherrer Institute meson factory. An experimental setup (see Fig. 1) developed for studying the muon-catalysed nuclear fusion reaction $d\mu^3\text{He} \rightarrow \alpha + \mu + p$ (14.6 MeV)$^{22}$ was used to measure $S_{He/D}$.

The body of the cryogenic gas target was made of pure Al in the form of a sphere 250 cm$^3$ in volume. There were five kapton windows 55 to 135 $\mu$m thick in the target body. The entrance window for the muon beam was 45 mm in diameter, its kapton was pressed with a stainless steel flange with a 1-mm-thick gold ring inserted in it. The other four windows were arranged in a circle and were intended for detection of charged products of fusion reaction in the $d\mu^3\text{He}$ reaction and muonic X-rays from $\mu$He atoms. Electrons from the decay of muons stopped in the target were detected by four pairs of plastic scintillator counters (E) installed around the target. The scenario of the experiment was as follows. First, the target was filled with a D/3He mixture at the den-

- Run Target Temp. Pressure $\varphi$ $C_{He}$ $N_{He}$
- 1 3He 32.9 6.92 0.0363 100 1.3625
- 2 3He 6.85 0.0359 0.7043
- 3 6.78 0.0355 0.7507
- 4 6.43 0.0337 0.4136
- 5 D/3He 32.8 5.11 0.0585 4.96 8.875

Information on the distribution of muon stops in the target volume in experiments with pure 3He and with the D/3He mixture can be gained from analysis of time distributions of muon decay electrons in 3He and D/3He targets

$$\frac{dN_{He}}{dt} = B_{Al}e^{-\lambda_{Al}t} + B_{Au}e^{-\lambda_{Au}t} + B_{He}e^{-\lambda_{He}t} + B,$$  

$$\frac{dN_{D/3He}}{dt} = F_{Al}e^{-\lambda_{Al}t} + F_{Au}e^{-\lambda_{Au}t} + F_{D/3He}e^{-\lambda_{D/3He}t} + F,$$  

where $B_{Al}$, $B_{Au}$, $B_{He}$, $F_{Al}$, $F_{Au}$ and $F_{D/3He}$ are normalized amplitudes, $B$ and $F$ are the levels of accidental coincidences, and $\lambda_{Al}$, $\lambda_{Au}$, $\lambda_{He}$, $\lambda_{D/3He}$ are the rates of muon disappearance in the target wall material and in the target gas.

Measuring the normalized partial amplitudes $B_{He}$ and $F_{D/3He}$ and knowing the muon decay electron detection efficiency averaged over the muon energy distribution, we can determine the number of muon stops in 3He and the D/3He mixture.

Comparing the results of the analysis of the data obtained under different experimental conditions we introduced a quantity $R$ for convenience. $R$ is a ratio between the number of electrons from decays of muons stopped in 3He (or in D/3He mixture) and the number of incident muons

$$R = \frac{N_{e}}{N_{\mu}}. \quad (10)$$

The scenario of the experiment was as follows. First, the target was filled with a D/3He mixture at the density $\varphi_{mix} = 0.0585$ and the initial muon beam momentum $P_{\mu}$ was varied to find its value corresponding to the maximum $R$. This value of $R$ corresponded to the highest density of muon stops in the gas at the center of the target. Then the target was filled with pure 3He to the pressure at which the number of stops in the target approximately corresponded to the number of muons entering the D/3He mixture.
exact, at which the numbers \( N^\phi_{He}^D/^{3}He \) and \( N^\phi_{He}^D/^{3}He \) of detected electrons from decays of muons stopped in the gas (in \(^3\)He and D/\(^3\)He mixture) were rather close. The \(^3\)He pressure in the filled target was selected using the program for calculation of muon energy loss on the passage of the muons through various materials [27].

To find out how the ratio \( R \) varies with the \(^3\)He density, four runs were carried out with the helium density varying in the interval 1%–7% from run to run (see Table I).

To find the number of muon stops in runs with \(^3\)He and the D/\(^3\)He mixture, time distributions of muon decay electrons were approximated by expressions [8] and [9] (see ref. [24] for more detailed description). Table II presents the numbers of detected muon decay electrons as well as the ratios \( R = N_e/N_\mu \) measured in runs 1–5 with pure helium and D/\(^3\)He mixture. The results of the measurement are also shown in Fig. 4 where four experimental points of \( R \) for pure helium versus target density are plotted. The abscissa of the intersection point of \( R(\varphi_{He}) \)-dependence with the horizontal line representing the \( R(\varphi_{mix}) \) value for the D/\(^3\)He mixture is just the one to determine the value of the equivalent helium density \( \varphi_{He} \).

In order to evaluate the character of \( R \)-dependence on \( \varphi_{He} \) the auxiliary Monte Carlo calculations were performed for our experimental conditions. The result of the simulation (dash-dotted line in Fig. 4) shows the non-linearity of the \( R \)-dependence.

\[
S_{He/D} = 1.66 \pm 0.04.
\]

As was mentioned earlier, the fact of the identity of the muon stop distributions for the D/\(^3\)He target at \( \varphi_{mix} \) and the He target at \( \varphi_{He} \) is crucial for our analysis. There are noteworthy points confirming this fact:

(i) The numbers of muon stops in the entrance ring of Au and the target walls of Al are equal (per incident muon) in both cases;

(ii) The ratios between the numbers of stops in the target walls and the gas are equal in both cases:

\[
N_{\mu}^A(\varphi_{He})/N_{\mu}^D(\varphi_{He}) = N_{\mu}^A(\varphi_{mix})/N_{\mu}^D(\varphi_{mix}),
\]

\[
N_{\mu}^A(\varphi_{He})/N_{\mu}^D(\varphi_{He}) = N_{\mu}^A(\varphi_{mix})/N_{\mu}^D(\varphi_{mix}).
\]

An additional remark concerning the interpretation of our measurement can be made. It is clear that the muon slowing-down and subsequent atomic capture are closely connected to each other. A discussion presented in Appendix A shows that such connection is so close that allows us to enlarge the interpretation of the measurement result from the point of view of the atomic muon capture. Concluding, we state that the result of the experiment in question is a ratio \( S_{He/D} \) of specific stopping powers of helium and deuterium atoms while, on the other hand, this quantity is phenomenologically equal to a reduced ratio of probabilities, \( A \), for muon capture by helium and deuterium atoms.

**APPENDIX A: MEAN RATIO OF STOPPING POWERS.**

Using notations

\[
\nu(E) = \frac{1}{\int_{0}^{E_{in}} \frac{1}{s_{He}(E)} dE},
\]

\[
G(E) = \frac{\varphi_{He}}{\varphi_{mix}(S(E))^{-1}C_{D} + C_{He}}.
\]

we can rewrite the equality of ranges [10] as

\[
\int_{0}^{E_{in}} \nu(E) G(E) dE = \overline{\varphi} = 1.
\]

Two components of the integrated function in Eq. A3 depend on the muon energy \( E \) in a quite different manner as is seen in Fig. 6.

The weighting function \( \nu(E) \) (normalized to unity) is strongly energy dependent and decreases roughly linearly with decreasing energy. \( G(E) \) (energy dependent via \( S(E) \)) is, contrary to \( \nu(E) \), approximately constant in a wide energy region. In Fig. 6 the calculated ratio of the muon ranges in D/\(^3\)He and pure helium-3 targets \( \overline{\varphi} = \int_{0}^{E_{in}} \nu(E) G(E) dE \) as a function of the initial muon energy \( E_{in} \) is presented. For given density, \( A \), with the ratio \( \varphi_{mix} \) at our level of accuracy the value of the stopping power ratio of helium-3 and deuterium atoms is

\[
S_{He/D} = 1.66 \pm 0.04.
\]

From the analysis of the data presented in Fig. 6 the equivalent helium density was found: \( \varphi_{He} = 0.0363 \pm 0.0005 \). A detailed presentation of the calculation is given in Appendix B.
TABLE II: Ratio $R$ measurements for runs 1 – 5. $N_\mu$ is the number of muons entering the target and $N_e$ is the number of detected electrons from muon stops in the $^3$He and $\text{D}/^3\text{He}$ targets.

| Run | Target     | $\varphi$ [LHD] | $N_\mu$ [$10^6$] | $N_e$ [$10^6$] | $R$ [$10^{-3}$] |
|-----|------------|-----------------|-----------------|----------------|-----------------|
| 1   | $^3$He     | 0.0363          | 1.3625          | 0.5302 (14)    | 0.3891 (10)     |
| 2   | $^3$He     | 0.0359          | 0.7043          | 0.2765 (10)    | 0.3926 (14)     |
| 3   | $^3$He     | 0.0355          | 0.7507          | 0.2975 (10)    | 0.3963 (14)     |
| 4   | $^3$He     | 0.0337          | 0.4136          | 0.1657 (8)     | 0.4007 (18)     |
| 5   | $\text{D}/^3\text{He}$ | 0.0585          | 8.875           | 3.4635 (35)    | 0.3903 (4)      |

**FIG. 5**: The functions $\nu(E)$ and $G(E)$ (formulae A1 and A2, respectively). $G(E)$ is calculated for the densities $\tilde{\varphi}_{^3\text{He}} = 0.0342$, $\varphi_{\text{mix}} = 0.0585$.

**FIG. 6**: Ratio of muon ranges in $\text{D}/^3\text{He}$ mixture and pure helium-3 targets $\overline{G} = \int_0^{E_{\text{in}}} \nu(E) G(E) dE$ calculated for different initial muon energies $E_{\text{in}}$, for three helium-3 target densities: 0.0335, 0.0342, 0.0349. The real energy spectrum of muons entering the targets is also shown (top).

of $E_{\text{in}}$. It is a consequence of the behaviour of the integrated function (or, in other words, due to similar dependence of deuterium and helium stopping powers on the muon energy). In the energy interval 1.8 – 2.3 MeV (50 % of beam muons belong to this interval) the relative change of $G$ is 0.4 %, and for interval 1.3 – 2.7 MeV (90 % of muons) the respective change is 1 %.

The quantity $\overline{G}$ in Eq. A3 represents the ratio of the ranges of muons with the initial energy $E_{\text{in}}$ in $\text{D}/^3\text{He}$ mixture and in pure $^3\text{He}$. Basically, equality A3 is fulfilled for a given energy $E_{\text{in}}$ for especially chosen $\tilde{\varphi}_{^3\text{He}}$ (as is seen in Fig. 6). For another energy the other density $\varphi_{^3\text{He}}$ should be, in principle, adjusted. But as can be seen from Fig. 6, such uncertainty in $\varphi_{^3\text{He}}$ is very small (less than 1 % in the range of our muon energy spectrum) and can be neglected.

In view of the above considerations it is reasonable to use an approximation

$$G \approx G(\overline{S(E)}) \approx G(S(\overline{E})),$$

(A4)

where $S(\overline{E})$ is the ratio of the atomic stopping powers taken for the average energy of the initial muon spectrum $\approx 2$ MeV. Then from eqs. A3 and A4 follows the equality

$$\frac{\tilde{\varphi}_{^3\text{He}}}{\varphi_{\text{mix}} S^{-1} C_D + C_{^3\text{He}}} = 1,$$

(A5)

and finally formula (7).

**APPENDIX B: ATOMIC CAPTURE**

Slowed-down muons are captured by the target atoms and finally end their life decaying in the atomic orbit 2s or 2p.

An alternative phenomenological interpretation of our measurement is the following. Each muon stop in the target gas is followed by an atomic capture either on a deuterium atom or on a helium atom. We identify the stopping event with an atomic capture event because we detect the decay electrons appearing after the muon is captured (electron decay in flight can be neglected as the slowing down time is about 1 ns, the probability of such decay is $\sim 10^{-4}$). The number of decay electrons, which appear as the consequence of muon stop at a given point of the target, depends on the density of atoms and on the probability of the atomic muon capture.

Let $N_\mu$ muons enter the target with a given initial energy distribution. Through a volume $\Delta V$ located at any given point of the target there pass $\Delta N_\mu$ muons. A part of them, $\Delta N_s$, having a sufficiently low energy due to slowing-down, are captured in $\Delta V$ and produce decay electrons. These muons which are not captured in $\Delta V$ continue to slow down and are stopped at another point of the target. The ratio of muons captured in such a way is

$$R = \frac{\Delta N_s}{\Delta N_\mu} = \frac{\Delta N_s}{\Delta N_\mu} = \frac{\overline{G}}{G(\overline{E})} = \frac{\tilde{\varphi}_{^3\text{He}}}{\varphi_{\text{mix}} S^{-1} C_D + C_{^3\text{He}}}.$$
electrons (i.e. the number of stopped and then captured muons) in $\Delta V$ is proportional to the number of entering muons $\Delta N_\mu$ and to the muon capture probability described by the capture cross section $\sigma_c$. The mean muon capture probability in $\Delta V$ is $\Sigma_c \Delta x$, where $\Sigma_c = n(H)\bar{\sigma}_H + n(D)\bar{\sigma}_D$ is the macroscopic capture cross section, $n$ are the densities of helium and deuterium atoms, $\bar{\sigma}_H$ and $\bar{\sigma}_D$ are the muon capture cross sections for helium and deuterium atoms, respectively (averaged over the muon energy), and $\Delta x$ is thickness of the volume $\Delta V$ along the direction of the muon beam. Under the assumption that the muon atomic capture cross sections $\sigma_H(E)$, $\sigma_D(E)$ are the same in both cases (monatomic or mixture target), and do not depend on the He concentration, the respective numbers of the captured muons can be written as

$$\Delta N_{\text{stop}}^{He} = \Delta N_\mu n_0 \varphi_H \bar{\sigma}_H \Delta x,$$

(B1)

$$\Delta N_{\text{stop}}^{\text{mix}} = \Delta N_\mu n_0 \varphi_{\text{mix}} (C_D \bar{\sigma}_D + C_H \bar{\sigma}_H) \Delta x,$$

(B2)

for a pure helium-3 target and for a target with a D+^3He mixture, respectively.

For a chosen density of the pure helium target, $\bar{\rho}_H$, the spatial stopping distribution is the same as for the mixture target (such a situation is illustrated in Fig. 8). Then, for the same volumes $\Delta V$ in both targets, the number of stops in helium the target with density $\bar{\rho}_{\text{mix}}$ is equal to the number of stops in the mixture with the density $\rho_{\text{mix}}$

$$\Delta N_{\text{stop}}^{He} = \Delta N_{\text{stop}}^{\text{mix}},$$

(B3)

Since the above local equality is valid for any point of the target we can rewrite it (using eqs. B1 and B2) as a general relation

$$\varphi_H A = \varphi_{\text{mix}} (C_D + A C_H),$$

(B4)

where

$$A = \frac{\bar{\sigma}_H}{\bar{\sigma}_D}$$

(B5)

is the ratio of the probabilities of muon capture by helium-3 and deuterium atoms. Rewriting Eq. (B4) in the form

$$A = \frac{C_D \varphi_{\text{mix}}}{\varphi_H - C_H \varphi_{\text{mix}}},$$

(B6)

one obtains the formula for the quantity $A$, which is equivalent to Eq. 7.

From the above considerations and taking, in particular, into account the identity of the relations 4 and 8, one can state that the value of the atomic stopping power ratio $\bar{\rho}$, which we measure in our experiment, is also (under indicated restrictions) a value of the reduced probability ratio, $A$, for the muon capture by helium-3 and deuterium atoms.

ACKNOWLEDGMENTS

We are thankful to P. Knowles, F. Mulhauser, L.A. Schaller, H. Schneuwly, V.F. Boreiko, W. Czapinski, M. Filipowicz, V.N. Pavlov, C. Petitjean, and V.G. Sandukovsky for very useful discussions and for their help during the data taking period. This work was supported by the Russian Foundation for Basic Research, Grant No. 01–02–16483, the Polish State Committee for Scientific Research, the Swiss National Science Foundation, and the Paul Scherrer Institute.

[1] V. I. Petrukhin and V. M. Suvorov, Zh. Eksp. Teor. Fiz. 70 (1976) 1145.
[2] V. M. Bystritsky et al., Zh. Eksp. Teor. Fiz. 84 (1983) 1257.
[3] M. Bubak and V. M. Bystritsky, Preprint JINR E1-86-107, Dubna, 1986.
[4] Yu. G. Budyanov et al., Yad. Fiz. 5 (1967) 830.
[5] A.V. Bannikov et al., Nuclear Physics A403 (1983) 515.
[6] F. Kottman, in: Muonic Atoms and Molecules, eds. L.A. Schaller and C. Petitjean (Birkhuser, Basel, 1993) p. 219.
[7] V. M. Bystritsky et al., Kerntechnik 58 (1993) 185.
[8] F. Kottman, in: Muonic Atoms and Molecules, eds. L.A. Schaller and C. Petitjean (Birkhuser, Basel, 1993) p. 219.
[9] V. M. Bystritsky, A.V. Kravtsov, and N.P. Popov, Muon Catalyzed Fusion 5/6 (1990/1991) 487.
[10] G.Ya. Korenman and S.I. Rogovaya, Yad. Fiz. 22 (1975) 754.
[11] G.Ya. Korenman and S.I. Rogovaya, J. of Phys. B, 13 (1980) 641.
[12] G.Ya. Korenman and S.I. Rogovaya, J. of Radiation Effects, 46 (1980) 189.
[13] J. S. Cohen, et al., Phys. Rev. A, 27 (1983) 1821.
[14] G.Ya. Korenman and V.P. Popov, in: Muons and pions in matter, JINR, D14-87-799 (Dubna, 1987) p. 418.
[15] V.K. Dolinov et al., Muon Cat. Fusion 4 (1989) 169.
[16] G. Ya. Korenman et al., Muon Catalyzed Fusion 5/6 (1990/1991) 49.
[17] G. Ya. Korenman et al., Muon Catalyzed Fusion 7 (1992) 179 and references therein.
[18] G. Ya. Korenman et al., Hyperf. Interactions 101/102 (1996) 81.
[19] G.A. Fesenko, G. Ya. Korenman, Hyperf. Interactions 101/102 (1996) 91.
[20] J.S. Cohen, Rep. Prog. Phys. 67 (2004) 1769.
[21] E. Fermi, E. Teller, Phys. Rev. 72 (1947) 399.
[22] V. M. Bystritsky et al., Phys. Rev. A 69 (2004) 012712.
[23] V. M. Bystritsky et al., Phys. Rev. A 71 (2005) 032723.
[24] V.M. Bystritski et al., Eur. Phys. J. D, 38 (2006) 455.
[25] V.F. Boreiko et al., Nucl. Instr. Meth. A 416, (1998) 221.
[26] R. Jacot-Guillarmot, Stopping Code, University of Fribourg (1997), unpublished.
[27] J.F. Ziegler, J.P. Biersack, and U. Littmark, The Stopping and Ranges of Ions in Matter, Vol. 1 (1985) Pergamon Press, New York.
A muonic atom is formed in an excited state, then the muon fast cascades to the ground state. The muon transfer to another type of atom is also possible during the cascade but such transfer has no significance for the electron detecting. Only primary atomic capture is crucial for the appearing of decay the electron which is for us an indicator of the muon stop. The cascade also does not change the coordinate of the stopping point because the cascading time is negligibly small.

A small part of muons can survive the atomic capture without decay in the atomic orbit. It is a case when the muon is freed in the result of the chain reaction with $d\mu^3He$ molecule formation and subsequent nuclear fusion. Such muons can be stopped again or escape the target. In any case, such rare events can be neglected in our considerations.