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EXPERIMENTAL ESTIMATES FOR MUON TRANSFER RATES FROM EXCITED pμ-ATOMS TO ^{4}He NUCLEI

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Экспериментальные оценки скоростей перехвата мюонов из возбужденных состояний $p\mu$-атомов к ядрам ^4He

Проанализированы данные эксперимента со смесью $H_2+{}^4He$ с целью определения скорости перехвата мюонов из возбужденных состояний $p\mu$-атомов к ядрам гелия. Обнаружено, что для n = 3, 4, 5 скорости составляют: $\lambda^{(3)} = (2 \pm 7)10^{10}$ c^{-1}; $\lambda^{(4)} = (16 \pm 13)10^{11}$ c^{-1}; $\lambda^{(5)} = (75 \pm 60)10^{11}$ c^{-1}. Обсуждается программа дальнейших исследований μ-атомных и μ-молекулярных процессов в смеси изотопов водорода и гелия.

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Experimental Estimates for Muon Transfer Rates from Excited $p\mu$-Atoms to ^4He Nuclei

The data of the experiment with the mixture $H_2+{}^4He$ are analyzed in order to estimate muon transfer rates from the excited states of $p\mu$-atoms to helium. The rates for n = 3, 4, 5 were found to be equal: $\lambda^{(3)}=(2 \pm 7)10^{10}$ s^{-1}; $\lambda^{(4)} = (16 \pm 13)10^{11}$ s^{-1}; $\lambda^{(5)} = (75 \pm 60)10^{11}$ s^{-1}. The program for further investigations of the μ-atomic and μ-molecular processes in the mixture of hydrogen and helium isotopes is discussed.

Introduction

During the last several years the study of μ-atomic and μ-molecular processes in mixtures of hydrogen and helium isotopes has been extensively carried out experimentally[1-11] and theoretically[12-20]. The interest for this study was stimulated by the experimental observation of a theoretically predicted new phenomenon - molecular charge exchange of the ground state muonic hydrogen on helium nuclei:

$$H\mu + He \longrightarrow [(H\mu He)^{*}e]^{+} + e^{-} \begin{cases} (H\mu He)^{++} + e^{-} & (1a) \\ (H\mu He)^{++} + e^{-} + \gamma\ (6.85\ \text{keV}) & (1b) \end{cases}$$

$$(H\mu He)^{++} \longrightarrow He\mu + H \qquad (1c)$$

$$H \equiv p,\ d,\ t, \qquad He \equiv {}^{3}He,\ {}^{4}He.$$

The study was further stimulated by the observation of muon transfer from excited states of muonic hydrogen. As followed from[3], muon transfer rate from the ground state is too large as compared with earlier experimental results[21] and calculations[22]. It became evident, that further study of μ-atomic and μ-molecular processes in the mixtures of hydrogen and helium isotopes is necessary to obtain unambiguous information on the parameters of these processes. Two circumstances are important here. The first one is that information about muon transfer from muonic hydrogen to helium nuclei will allow one to understand the experimental data on muon catalyzed fusion in $D_2 + T_2$ mixture (which produces helium as a result of the natural tritium decay and of fusion reactions), as well as to estimate the necessary extent of mixture cleansing of helium accumulated. Secondly, the rates of the μ-atomic and μ-molecular processes are necessary to describe correctly the kinetics of the cascade transitions and the thermalisation process of muonic hydrogen.

Up to now, the measurements are performed of the muon transfer from the ground state of pμ, dμ, and tμ-atoms to ${}^{4}He$[1,3,7,8], ${}^{4}He$, ${}^{3}He$[2,5,6,10] and ${}^{3}He$[4] respectively. As to the partial muon transfer rates from the excited states of muonic hydrogen isotopes to helium, only few experimental boundary estimates, averaged over excited states of the muonic atom, are now available [1,2].

The kinetics of excited muonic hydrogen in hydrogen-helium mixture has been considered in [18], a method for determination of muon transfer rates from the excited states of muonic hydrogen to helium having been proposed. Here we made an attempt to obtain the rates of the muon transfer from excited pμ-atoms to ${}^{4}He$ nuclei, analyzing the data experimentally measured in[3].

Data analysis

Let us remember the conditions of the experiment[3] and the method of measurement of the characteristics of muon transfer process. Fig.1 shows the scheme of the processes which take place when a negative muon stops in the H_2 + He + Xe mixture. One should note, that the low concentration of the probe gas - xenon in[3] allowed one to neglect the direct muon atomic capture by xenon as well as the influence of xenon admixture upon the kinetics of the cascade transitions in pμ-atoms.

The experiment was performed at the muon beam of the JINR synchrocyclotron using the gas target with internal scintillators, aimed to detect muons stopping in the target volume. The target was filled, successively, by pure hydrogen, by H_2+ Xe mixture (relative atomic xenon concentration $\approx 10^{-4}$) and by H_2+ Xe + ${}^{4}He$ mixture at different values of the mixture density φ and relative helium concentrations C_{He}. Decay electrons from the muon decay were registered at each run, as well as X-rays from Xeμ-atoms, formed due to muon transfer from muonic hydrogen to xenon nuclei.

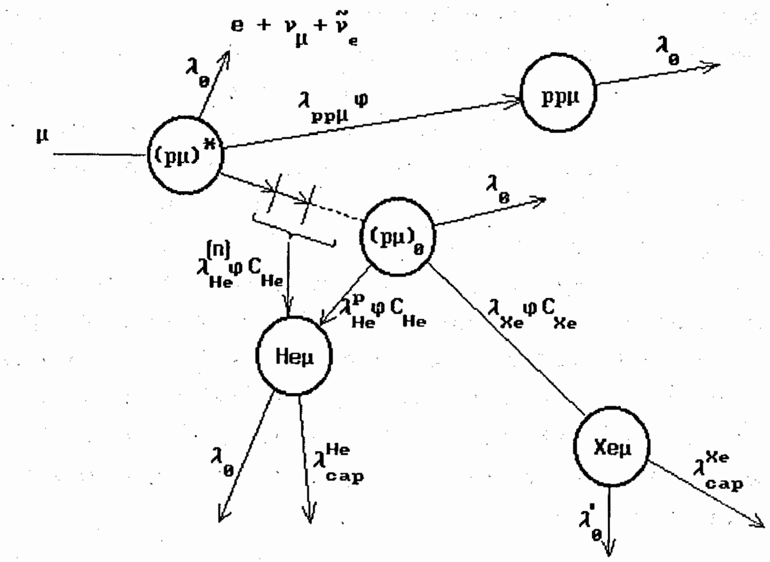

Fig 1

The processes involved when a muon stops in the $H_2 + {}^4He + Xe$ mixture

λ_o = 0.455 . 10^6 s^{-1} free muon decay rate;

$\lambda_{pp\mu}$ - $(pp\mu)$ - molecule formation rate;

λ_{Xe} - muon transfer rate from the $p\mu$ - atom to Xe nucleus;

λ^P_{He} - muon transfer rate from the ground state $p\mu$ - atom to helium nucleus;

C_{He}, C_{Xe} - relative atomic concentrations of He and Xe;

φ - density of the mixture $H_2 + {}^4He + Xe$ with respect to the density of liquid hydrogen $n_0 = 4.25\ 10^{22}$ cm^{-3};

$\lambda^{(n)}_{He}$ - muon transfer rate from the excited $p\mu$-atom in the state with the principal quantum number n to helium nucleus;

$\lambda^{He}_{Cap}, \lambda^{Xe}_{Cap}$ - rates of muon atomic capture by helium and xenon nuclei, respectively;

λ'_o - rate of the muon decay from the 1s-state of the $Xe\mu$-atom.

The analysis of time distributions for decay electrons and X-rays allowed us to obtain the probability for muon, stopped in the mixture $H_2 + He$, to be captured by hydrogen atom and the muonic atom thus produced to reach the ground state:

$$W = W_o W_H . \qquad (1)$$

W_H is the probability of $p\mu$-atom formation as a result of the muon atomic capture by hydrogen, $W_o \equiv q_{1s}$ is the probability for the muonic atom formed to reach the ground state (ground state population). This population is determined not only by the helium concentration and target density, but also by the kinetics of the excited $p\mu$-atom, taking into account the de-excitation and muon transfer processes. The value W_H is defined by

$$W_H = \frac{1}{1 + AC'_{He}} \qquad (2)$$

where A is the ratio of the rates of the muon atomic capture by helium and hydrogen, $C'_{He} = N_{He}/N_H$ - relative atomic helium concentration; N_{He}, N_H - the amount of helium and hydrogen atoms in the mixture $H_2 + {}^4He + Xe$.

Table 1

Run Number	P_{H_2} (Atm)	P_{He} (Atm)	W	$W_0 = q_{1s}$
1	24.60	2.4600	0.87 (0.03)	0.935 (0.080)
2	24.60	5.4120	0.70 (0.04)	0.815 (0.070)
3	16.50	6.2700	0.50 (0.02)	0.662 (0.041)
4	24.60	14.2680	0.33 (0.05)	0.493 (0.079)
5	16.50	12.5400	0.28 (0.03)	0.461 (0.056)
6	20.00	18.4000	0.25 (0.02)	0.446 (0.044)
7	16.50	23.1000	0.13 (0.02)	0.285 (0.050)
8	20.00	35.6000	0.12 (0.02)	0.323 (0.055)

The measured values of W are shown in Table 1 together with data, that illustrate the experimental conditions.

Knowing C'_{He} and A = 1.7 ± 0.2 (which is the average over the results of [/17,23,24/]), we have obtained the rates of the muon atomic capture by hydrogen, W_H, with the help of eq. (2), and then from eq. (1) the ground state population $q_{1s} = W_o$. To obtain muon transfer rates from these experimental q_{1s} values one should consider the kinetics of the muonic hydrogen cascade in $H_2 + {}^4He$ mixture. We assumed the cascade scheme to be that used in previous papers [/14,18/] (see fig.2). As seen from fig. 2, the initial population of the pμ-atom state with n = 5 is assumed to be $q_5 = 1$ because of the high rates of Auger deexcitation for n > 5 as compared with muon transfer rates. We assumed also that the muon transfer rate for a given quantum number n does not depend on the orbital quantum number. As in [/18/], we neglected the energy dependence of muon transfer rates. We did not take in to account also the difference in the cross sections of the external Auger process on hydrogen and helium atoms. The rate of the Stark deexcitation of the 2s-state of the pμ-atom was taken to be $\lambda_{ind} \cong 0.04\ \varphi . 10^{11} s^{-1}$ for thermal energy 0.04 eV.

As in ref. [/15,18/], for n = 2 we considered muon transfer only from the 2s-state, corresponding to the attraction between the pμ-atom and helium nucleus.

Assuming nonthermalisation of pμ-atoms in the 2s and 2p-states, we used the following values of the Stark deexcitation rates [/14/]:

$$\lambda\ (2s \longrightarrow 2p) = 32\ \varphi\ .\ 10^{11} s^{-1} \qquad (\varepsilon_{p\mu} = 0.5\ \text{eV})$$
$$\lambda\ (2s \longrightarrow 2p) = 48\ \varphi\ .\ 10^{11} s^{-1} \qquad (\varepsilon_{p\mu} = 1\ \text{eV})$$
$$\lambda\ (2p \longrightarrow 2s) = \frac{1}{3}\ \lambda\ (2s \longrightarrow 2p).$$

Though the deexcitation rate of the 2s-state has a sharp energy dependence, this fact hardly influences the value q_{1s}, because, according to the estimates [/25/], the 2s-population is rather low (5 ÷ 7 %) for our experimental conditions ($C'_{He} \cong 0.05 \div 0.5$; $\varphi \cong 0.03 \div 0.05$).

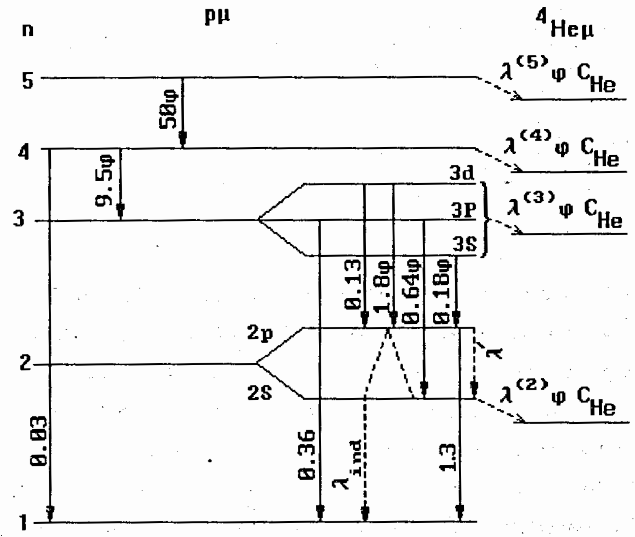

Fig. 2

The scheme of the pμ-atom cascade in the H_2 + He mixture. Transition rates are given in units $10^{11} s^{-1}$; λ_{Ind} and λ' are Stark deexcitation rates; $\lambda^{(1)} \div \lambda^{(5)}$ – muon transfer rates from the pμ-atom to helium nucleus.

For a given scheme of the cascade, one can write:

$$q_{1s} = a_1 \left\{ a_2 \left[\frac{5}{9} a_3 + \frac{1}{9} a_4 + \frac{1}{3} a_5 a_6 + \frac{1}{3} a_7 \right] + a_8 \right\} \qquad (3)$$

$$a_1 = \frac{\lambda^{5-4}_{Aug}\ \varphi}{\lambda^{5-4}_{Aug}\ \varphi + \lambda^{(5)} \varphi\ C_{He}}; \qquad a_2 = \frac{\lambda^{4-3}_{Aug}\ \varphi}{\lambda^{4-3}_{Aug}\ \varphi + \lambda^{4-1}_{rad} + \lambda^{(4)} \varphi\ C_{He}};$$

$$a_3 = \frac{\lambda^{3d-2p}_{rad} + \lambda^{3d-2p}_{Aug}\ \varphi}{\lambda^{3d-2p}_{rad} + \lambda^{3d-2p}_{Aug}\ \varphi + \lambda^{(3)} \varphi\ C_{He}}; \qquad a_4 = \frac{\lambda^{3s-2p}_{Aug}\ \varphi}{\lambda^{3s-2p}_{Aug}\ \varphi + \lambda^{(3)} \varphi\ C_{He}};$$

$$a_5 = \frac{\lambda^{3p-2s}_{Aug}\ \varphi}{\lambda^{3p-2s}_{Aug}\ \varphi + \lambda^{3-1}_{rad} + \lambda^{(3)} \varphi\ C_{He}}; \qquad a_6 = \frac{\lambda_{ind}}{\lambda_{ind} + \lambda^{(2)} \varphi\ C_{He}};$$

$$a_7 = \frac{\lambda^{3p-1s}_{rad}}{\lambda^{3p-1s}_{rad} + \lambda^{3p-2s}_{Aug}\varphi + \lambda^{(3)}\varphi C_{He}};$$

$$a_8 = \frac{\lambda^{4-1}_{rad}}{\lambda^{4-3}_{Aug}\varphi + \lambda^{4-1}_{rad} + \lambda^{(4)}\varphi C_{He}}.$$

Here $\lambda^{(n)}$ are muon transfer rates (to be determined) from the $p\mu$-atom in the state with principal quantum number n to a helium nucleus; λ_{Aug} – Auger deexcitation rates (all these rates are reduced to the liquid hydrogen density); λ_{rad} – the rates of the radiation transitions.

As a result of the least squares fitting of experimental data the following values of the muon transfer rates were obtained: ($\chi^2 = 4.9$)

$\lambda^{(3)} = (2 \pm 7).10^{10}.s^{-1}$; $\lambda^{(4)} = (16 \pm 13).10^{11}.s^{-1}$;
$\lambda^{(5)} = (75 \pm 60).10^{11}.s^{-1}$.

The χ^2 value turned out to be independent of the value $\lambda^{(2s)}$, which can be explained by the low population of the 2s-state for our experimental conditions. For the same reason it was impossible to determine the energy of $p\mu$-atoms in the 2s state: the fits with $\varepsilon_{p\mu}$ equal for 0.04 eV, 0.5 eV and 1 eV were indistinguishable. This means that to obtain the value $\lambda^{(2s)}_{He}$ and energy distribution of $p\mu$-atoms in the state n = 2 one should measure the intensity of K lines of the retarded X-rays from muonic hydrogen (2p ⟶ 1S transition after the Stark transition 2s ⟶ 2p) and muonic helium. Such experiments should be carried out at low density ($\varphi \le 10^{-5}$) and sufficiently high helium concentrations ($C_{He} \ge 0.5$).

To summarize the present work and the results of [/18/], one can formulate a program for further investigations of the kinetics of μ-atomic and μ-molecular processes, occurring in a mixture of hydrogen and helium isotopes.

1. Experiments with D_2 + He and T_2 + He mixtures for $\varphi = 0.05 \div 1$ and low helium concentrations ($C_{He} = 10^{-3} \div 5.10^{-2}$), when one may neglect the direct muon atomic capture by helium, will allow one to obtain with a reasonable accuracy q_{1s} values, muon transfer rates from the excited muonic deuterium and tritium to helium, as well as to check the scheme of the cascade transitions in muonic hydrogen atom.

2. Starting with the given cascade scheme in $d\mu$ and $t\mu$ atoms, one can obtain with good accuracy the probability of the direct muon atomic capture by helium from experiments with higher helium concentrations. We believe it possible to measure the A value (according to (2)) with the accuracy 2 ÷ 4 %.

3. Experiments at low density $\varphi \le 10^{-5}$ and high helium concentrations will allow to obtain muon transfer rate $\lambda^{(2)}$, as well as to get information on the energy distribution of muonic hydrogen atoms in the state with n = 2.

4. It is possible to evaluate transfer rates from $p\mu$ to He using experimental values of muon transfer rates from excited states of $d\mu$ atoms to He and more precise algorithm of transfer rates calculation.

5. Experiments with H_2 + He mixtures for a wide range of density and helium concentrations can give information on the muon transfer rate from the excited $p\mu$-atoms, as well as the probability of the direct muon atomic capture by hydrogen, and hence the A – value.

6. Comparing A – values obtained from experiments with H_2+ He, D_2+ He and T_2+ He mixtures will help to answer a question about the isotopic dependence of muon atomic capture by hydrogen isotopes .

7. Measurements with H_2+ He, D_2+ He and T_2+ He mixtures at various temperatures (20 K ≤ T ≤ 5000 K), densities and helium concentrations will give information about the contribution of resonant and nonresonant mechanisms of molecular muon transfer from muonic hydrogen to helium nuclei.

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