ОБЪЕДИНЕННЫЙ
ИНСТИТУТ
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ

Дубна

E15-99-149

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TIME-EVOLUTION OF CASCADE PROCESSES OF MUONIC ATOMS IN HYDROGEN-HELIUM MIXTURES

Submitted to «European Physical Journal – D»

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1999

1 Introduction

The processes induced by negative muon stopped in mixtures of hydrogen isotopes with admixtures of $Z > 1$ elements have been studied for some time already; however, some interesting questions about the processes remain open. Research of nuclear fusion in charge-asymmetric muonic molecules like $h\mu Z$ ($h \equiv p, d, t$ is a hydrogen isotope, Z is an isotope of helium, lithium, beryllium etc.) allows extending the energy region of investigation of strong interactions to very low energies ($eV \div keV$), which cannot be reached in accelerator experiments. The properties of strong interactions such as charge symmetry or isotopic invariance are all experimentally established mainly in the MeV region and, up to now, have only been extrapolated to the low-energy region [1].

The study of fusion reactions between light nuclei is important also for astrophysics. Specifically, this study is relevant to the nuclear reactions which took place in the process of primordial nucleosynthesis just after the Big Bang, and those occuring in stars, where light elements are produced. For example, in stars and in the Galaxy one finds a deficiency of light nuclei (except for ^4He) compared with predictions based on the theory of thermonuclear reactions and generally adapted models. To explain this phenomenon, modified star models are usually proposed, which assume that in the extrapolation of nuclear cross sections from accelerator energies to the astrophysical energy region ($\sim keV$) no resonances or other anomalies of the cross sections occur. It cannot be excluded, however, that nuclear cross sections have a resonance character, which could lead to intensive burning of light elements in stars [1].

Most theoretical and experimental studies of asymmetric muonic molecules have been devoted to the $h\mu He$ systems. Recently, the dynamics of muonic atom cascade in hydrogen-helium mixtures was considered in [2]. This is important [3] for the investigation of the nuclear fusion reactions: [1]

$$d\mu^3He \stackrel{\lambda_f}{\to} \begin{cases} \alpha + p(14.7MeV) + \mu \\ {}^5Li + \gamma(16.4MeV) + \mu \end{cases} \qquad (1)$$

and $d\mu^4He$

$$d\mu^4He \stackrel{\lambda_f}{\to} {}^6Li + \gamma(1.48MeV) + \mu\,. \qquad (2)$$

However, time-evolution of the cascade processes was not considered there. The experimental investigation of fast processes in muonic atoms became possible due to development of short-time technique and essential improvement of time-resolution of detectors for registration of nuclear radiation. The experimental information about characteristics of the cascade of muonic hydrogen could be obtained as a rule by the measurement of yields and time-distributions of the muonic x-ray of the hydrogen isotopes and $Z > 1$ admixtures in hydrogen targets [2]. Therefore, the comparison of experimental and theoretical yields and time-distributions of the muonic x-rays may allow one to test the description of the real muonic cascade. Consequently, the measurements of intensity of delayed K-lines could enable one to determine the population of the $2s$-state of muonic hydrogen as well as the scheme of the cascade used in the calculations.

The measurement of x-ray yields of muonic helium in hydrogen-helium mixtures enables one to obtain the muon transfer rates from hydrogen to helium (in comparison with experimental data obtained in pure hydrogen mixtures) and to check the scheme of the cascade. The comparison of the experimental and calculated relative intensities of K-lines, i.e. K_α/K, K_β/K and K_γ/K (where $K = K_\alpha + K_\beta + K_\gamma + K_\nu$) as well as the ratios of intensities K_α/K_β, K_β/K_γ etc. in pure hydrogen mixtures and those containing $Z > 1$ admixtures, can allow one to investigate the dynamics of muonic cascade. The determination of population of excited states of muonic hydrogen and muonic helium for different principal quantum number n in hydrogen-helium mixtures by measurement of the corresponding x-rays may let one to verify the scheme of muonic cascade as well as muon transfer process.

The analysis of time-evolution of muonic cascade should allow one to choose experimental conditions for which it is possible to obtain information about cascade needed for correct comparison with theory. Such time-evolution data can give very important additional

[1] Taking into account the importance of reactions (1) and (2) we shall mainly consider the dynamics of muonic cascade in deuterium-helium mixtures.

[2] In fact, information about dynamics of cascade could be improved by development of Auger spectroscopy. The measurement of time distributions of electrons of muon decay in muonic hydrogen could give additional information about muonic atom cascade in mixtures of hydrogen isotopes with $Z > 1$ admixtures.

information about exotic systems.

The present paper is devoted to determination of time-dependence of population of excited levels of muonic atoms during cascade deexcitation process as well as of the dependence of muon transfer rates to helium nuclei on target density ϕ and helium concentration C_{He}.

2 Cascade model

The number of $d\mu He$ molecules formed is proportional to the number of muonic deuterium atoms, $d\mu$, in the ground state, which is determined by the probability [2]

$$W = W_D \cdot q_{1s}^{He}, \tag{3}$$

where W_D is the probability of formation of $d\mu$ atom in the excited state (with principal quantum number $n \simeq \sqrt{m_\mu/m_e} = 14$) and q_{1s}^{He} is the probability of deexcitation of the muonic deuterium to its ground state (ground state population). Following [2] we determine

$$W_D = (1 + \frac{C_{He}}{C_D} A)^{-1}, \tag{4}$$

where C_D is deuterium concentration ($C_{He} + C_D = 1$) and A is the ratio of the muon capture rates for helium and deuterium: $A = 1.7 \pm 0.2$ [2] (the analogous ratio for protium and deuterium is equal 1.204 in $H_2 + D_2$ mixture [4]).

As shown in the previous investigations, the ground state of muonic atom is reached only by a fraction of formed originally excited muonic hydrogen atoms owing to muon transfer to heavier hydrogen isotopes or to $Z > 1$ nuclei, e.g. to He. As cascade evolution occurs in a very short time ($\leq 10^{-11} s$ at liquid hydrogen density, LHD) in the scale of muonic atom processes, the experimental information about numerous processes occuring during deexcitation of muonic atom is poor. At the same time, the theoretical predictions, especially concerning the early stages of the muonic cascade are also not fully determined [5]. Therefore, the research of alternative methods of obtaining information about W and corresponding W_D and q_{1s}^{He} is very important. The agreement between experimental and theoretical data obtained using analogous assumptions about the cascade scheme for pure hydrogen targets and hydrogen-helium mixtures could provide a basis to extend this scheme to consideration of time-evolution processes.

The basic cascade processes are the following [2,6,7]: radiative and Auger deexcitation, Stark mixing, Coulomb deexcitation, elastic scattering responsible for the thermalization of the muonic hydrogen and muon transfer from excited muonic hydrogen to other nuclei. According to [2,6] we assume constant energy $\varepsilon = 0.04 \div 2eV$ of the muonic atom during the cascade. As the accurate calculation of Auger and Coulomb deexcitation rates on helium nuclei are still absent, as well as the deexcitation rates of $2s$ level owing to Stark mixing with $2p$ level in the field of helium nucleus, we follow the approximation used in [2]. The corresponding Auger rates are approximated by $2\lambda_A$, where λ_A are calculated according to formula (8) of ref. [8] with replacement of ionization energy of the hydrogen atom (molecule) by helium ionisation energy, $I_{He} = 24.68eV$ (see Table 1 of [2]). The reaction rates for Coulomb deexcitation, Stark mixing, transitions between $2s$ and $2p$, and induced $2s \to 2p \to 1s$ transitions are supposed to be the same as those for collisions of muonic deuterium with tritium and are taken from [9] and [6], respectively. The rates of muon transfer from muonic deuterium to helium nuclei for $n \leq 5$ have been calculated in [10]. As there are no theoretical data for muon transfer to helium from $n > 5$, the corresponding values were used as in [2] to be same as the transfer rate for $n = 5$. According to [5] we suppose that the initial n distribution is peaked around $n = 12$, so our calculations of the cascade parameters are based on the solution of a system of kinetic equations with the initial population of the state $q_{12}^{He} = 1$ for the cascade scheme presented by Fig.1 with secondary radiative and Auger transitions taken from Table 1 in [2] and Table 15 in [11] recalculated for the muon mass.

We take into account the $3 \to 2$ Coulomb transition, which was not considered in [2,13], and Stark transitions between the sublevels with orbital angular momentum l for $n = 3$ i.e. between $3d$, $3p$ and $3s$ [12] [3]. We assume statistical population of l-sublevels for $n > 3$ [7a,b].

[3]The rates of Stark mixing were kindly provided to us by V.P.Popov.

3 Results of calculations

In order to verify cascade scheme of Fig.1 we compare some of its calculated characteristics with the experimental data for pure H_2 and D_2 as well as for their mixtures with He isotopes in a wide range of ϕ and C_{He}. For example comparison was done of the calculated and experimental data for relative intensities of K-lines of $p\mu$ and $d\mu$ atoms in pure H_2 and D_2, respectively, and for q_{1s}^{He}. The time-evolution of cascade processes is presented here for the first time, which can be very important for understanding the complex dynamics of muonic cascade. Earlier [2,13], we considered for comparison with experiments (see ref. [25] in [2]) only single characteristics of the cascade, q_{1s}^{He}, for $H_2 +^4 He$ at $\phi = (2.3 \div 4.5)\%$ and $C_{^4He} = 0.05 \div 0.5$. As follows from Fig.6 and Table 2 in [2] the agreement between theoretical and experimental q_{1s}^{He} is possible if one assumes $\varepsilon \sim 2 \div !5eV$. In the present paper we extend our consideration to comparison of our calculations of relative intensities of K-lines with the available experimental data. Such comparison requires inclusion of $3 \to 2$ Coulomb deexcitation which was ignored in [2,13].

However, there exists wide uncertainty in the calculation of Coulomb deexcitation rates obtained by different methods [9a,b,c]. In our calculations we use different assumptions about the contribution of Coulomb deexcitation to the cascade development by scaling its rate: $\lambda_C = \kappa\lambda$, where $\kappa = 1$ corresponds to Coulomb rates obtained in [9a].

We consider $3 \to 2$ Coulomb deexcitation rate as free parameter for fitting the calculated relative intensities of K_α, K_β and K_γ to corresponding experimental data in pure H_2 and D_2. The ratio of $4 \to 3$ and $3 \to 2$ rates is also obtained from fits to experimental intensities of the K-lines [4].

The ratios of other Coulomb deexcitation rates were taken from [9c] multiplied by corresponding correction factor. However, they influence only weakly the calculated intensities of K-lines and could be taken, in fact, from any of the paper [9a,b,c].

The results of our calculations of the different characteristics of muonic hydrogen cascade obtained for hydrogen-helium mixtures with Coulomb deexcitation rates from [9c] are presented in Figs 2-5. Figs 6 illustrates our calculation of K-line intensities for pure H_2 and D_2 with Coulomb deexcitation rates obtained by fitting the calculated results to experimental data.

Figs.2a-c show the results of calculations of $q_n^{He}(t,\phi)$ in $D_2 + {}^3He$ mixture obtained for $\varepsilon = 0.04eV$ with $C_{He} = 0.05$. As can be seen, the ground state $1s$ and the excited state $n = 3$ reach maximal populations for $t \geq 10^{-10}s$ and $t \simeq 10^{-10}s$, respectively.

The number of muons transferred to helium from muonic deuterium, $N_n^{tr}(t,\phi)$, has also been calculated for $\varepsilon = 0.04eV$ and

[4] Unfortunately the $4 \to 3$ Coulomb deexcitation rate was absent in [9a].

$C_{He} = 0.05$ in $D_2 + {}^3He$ (Figs.3a-c). The maximum number of transferred muons corresponds to $N_3^{tr}(t > 10^{-10}s) = 20\%$.

Fig.4 shows the results of our calculations for the relative K x-ray yields i.e. $I_{K_\alpha}(t,\phi)$ for $2p \to 1s$ transition, $I_{K_\beta}(t,\phi)$ for $3p \to 1s$ transition, $I_{K_\gamma}(t,\phi)$ for $4p \to 1s$ transition, and $I_{K_\nu}(t,\phi)$ for $(5p \to 1s) + (6p \to 1s) + (7p \to 1s) + \ldots$ transitions obtained for $\varepsilon = 0.04eV$ and $C_{He} = 0.05$ in $D_2 + {}^3He$.

Fig.5 demonstrates the agreement of our calculated q_{1s}^{He} with the experimental data for $H_2 + {}^3He$ ($\phi = 5.2\%$) and $H_2 + {}^4He$ ($\phi = 7.36\%$) mixtures [14].

The experimental q_{1s}^{He} data in $H_2 + {}^4He$ and $H_2 + {}^3He$ agree with the calculated ones within the experimental errors for $\varepsilon \sim 2eV$. The comparison for $H_2 + {}^4He$ at $\phi = (2.3 \div 4.5)\%$ [2,15] also indicates for $\varepsilon \sim 2 \div 5eV$as well as experimental data for q_{1s} in $H_2 + D_2$ mixture [16].

The ϕ-dependence of relative intensities of K-lines in pure H_2 and D_2 in the range $(10^{-5} \div 1)$ is presented in Fig. 6a and b, respectively, together with the experimental data of Refs. [17-24].

As can be seen in Fig. 6a for pure H_2, good agreement between theory and experiment is possible for the rate of Coulomb $3 \to 2$ transition $\sim 9 \cdot 10^{11} s^{-1}$ (LHD) that exceeds by a factor of about $1.5 \cdot 10^3$ the result of [9c] for $\varepsilon = 1eV$ and by about 100 that of [9b]. Our rate exceeds corresponding result of [9a] by a factor 9. If one assumes that muonic hydrogen in the $n = 3$ state is thermalized i.e. $\varepsilon = 0.04eV$, our $3 \to 2$ Coulomb rate exceeds by a factor of about 440 times the result of [9c], that of [9b] by ~ 30 and only by 2.7 that of [9a].

Fig.6b shows us, that for pure D_2, good agreement between theory and experiment is possible for the $3 \to 2$ transition rate $\sim 4.8 \cdot 10^{11} s^{-1}$ that exceeds by $\sim 2 \cdot 10^4$ correspondent result of [9c] for $\varepsilon = 1eV$ and by $\sim 5 \cdot 10^3$ for $\varepsilon = 0.04eV$. Unfortunately we cannot compare our results for $d\mu$ with data of [9a] as only mesic protium was considered there.

For $p\mu$ atoms the ratio of Coulomb rates of $3 \to 2$ and $4 \to 3$ transitions is smaller by a factor of 2 compared with $d\mu$ ones. At the same time the rate of $3 \to 2$ Coulomb transition of $p\mu$ atoms is two times larger than that of $d\mu$. The Coulomb transitions for $n > 4$ do not strongly influence the intensities of K-lines. The ratio of Coulomb rates for $3 \to 2$ and $4 \to 3$ transitions contradicts the results of [9c] being at the same time in good agreement with ones obtained in [9b].

It is necessary to note that the results of calculations of Coulomb deexcitation rates obtained in [9c] (corresponding to $\kappa \sim 0.01$ which gives a contribution to intensities of K-lines coincided, in fact, with $\kappa = 0$) evidently disagree with the experimental data for K_α and K_β intensities. It can be possibly explained by the fact that the method of complex plane is not applicable to nonresonant reaction of Coulomb deexcitation [9c] with great energy gain. The critique

of the approach of [9c] has also been given in [9b].

At the same time, the intensity of K_γ is not so sensitive to Coulomb deexcitation contribution, which, in fact, agrees also with Fig.3 in [17].

It is necessary to note that the $3 \to 2$ Coulomb transition is very important for the agreement of theory with experiment for K_α and K_β at least for $\phi > 10^{-3}$. The rates obtained from the analysis of K-line intensities significantly exceed the results of [9b,c] being, however, in better agreement with those of [9a].

The small disagreement of the calculated curves for K_β and K_γ for $p\mu$-atoms in Fig.6a with experimental data for density range $10^{-5} \div 10^{-4}$ and $10^{-2} \div 5 \cdot 10^{-2}$, respectively, can be possibly explained by absence in our consideration of any partial Stark transitions between l-sublevels for $n > 4$, which reflects, in fact, the assumption of statistical population of the corresponding l-sublevels. Except of this we do not consider partial Coulomb transitions $(n, l) \to (n-1, l-1)$ for $n \geq 4$ using only averaged Coulomb ones with statistical populations of l-sublevels of $n' = n - 1$. As for partial Coulomb transitions $3d \to 2p$, $3p \to 2s$ and $3s \to 2p$ we used averaged $3 \to 2$ rate with a statistical population of $3d$, $3p$ and $3s$.

The Coulomb transitions with $\Delta n = 2, 3...$ should probably be also taken into account in addition to $\Delta n = 1$, although their contribution is smaller at least by one order of magnitude [9a].

It is necessary to model the initial population of n and l which may importantly influence the populations of l-sublevels for $n = 2 \div 4$, being more important for Coulomb fraction of cascade deexcitation. Information about energy distribution of muonic atoms in the above mentioned states is also important.

One of the important problem is explanation of the high $3 \to 2$ transition rate by resonant mechanism for Coulomb deexcitation [7b] or by the possibility that molecular structure effects are more important at large ϕ.

The $3 \to 2$ and $4 \to 3$ Coulomb deexcitation should be comparable with the corresponding Auger transitions or exceed them, being also responsible for acceleration of mesic hydrogen [9b] observed in numerous experiments.

As relative intensities of K-lines depend less on ε the extraction of possible Coulomb deexcitation contribution by comparison with experiment is more definite than by analogous comparison for q_{1s}^{He}.

In conclusion, we would like to underline that the accurate analysis of main characteristics of muonic cascade in pure H_2 and D_2 as well as in their mixtures with helium isotopes in a wide range of ϕ and C_{He} was performed in the present paper by comparison with the corresponding experimental data. For q_{1s}^{He} good agreement between theory and experiment was obtained for $C_{^{3,4}He} = 0 \div 1$ and $\phi = 0 \div 1$ taking into account also the results of the previous paper [2].

Good agreement was also obtained for relative intensities of K_α, K_β and K_γ lines in pure H_2 and D_2. Moreover, the comparison of relative intensities of K_α and K_β lines with experiment enabled us to select Coulomb deexcitation rates in muonic atom cascade mainly in

favor of the results of [9a], indicated earlier also by Markushin et al. [7a,b]. However, our $3 \to 2$ Coulomb deexcitation rates obtained by fits to experimental data in Figs 6 exceed essentially the theoretical predictions, including [9a]. Possibly, it could be explained by poor information about the cascade parameters which are necessary for very small ϕ used in the fits presented in Figs 6.

At the same time the q_{1s}^{He} is not so sensitive to the values of Coulomb deexcitation rates, especially for small ϕ [7b] having also ε-dependence. The essential contribution of Coulomb deexcitation process could explain in natural way the epithermal contribution in the energy distribution of mesonic hydrogen, observed in numerous experiments (see e.g. Ponomarev et al. [9b]).

Investigation of dynamics of the muonic cascade in wide range of ϕ and C_{He} using the same experimental method is very important in order to eliminate possible systematic errors. The investigation of dynamics of muonic atom cascade at very small $\phi \sim 10^{-7}$ may enable one to verify the initial stage of the cascade, which is, of course, very important for following stages of cascade. In order to obtain more reliable information about the characteristics of cascade, taking into account our present analysis, it is necessary to perform additional experimental measurements of intensities of K-lines for $\phi = 0.1 \div 1$ and $\phi = 10^{-3} \div 10^{-2}$. It is also necessary to calculate the rates of Stark mixing and Coulomb deexcitation transitions between l-sublevels for all n. The realization of a multiparameter Monte-Carlo program is important for the analysis of all complex processes determining muonic cascade.

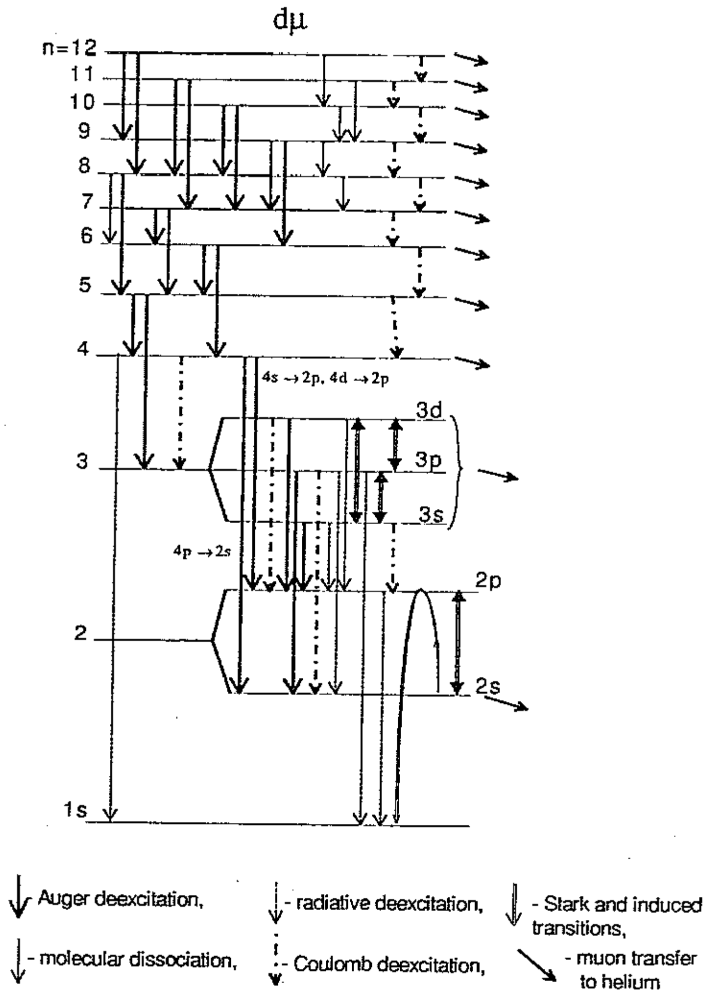

Fig.1. Scheme of the muonic atom cascade for muonic hydrogen atom.

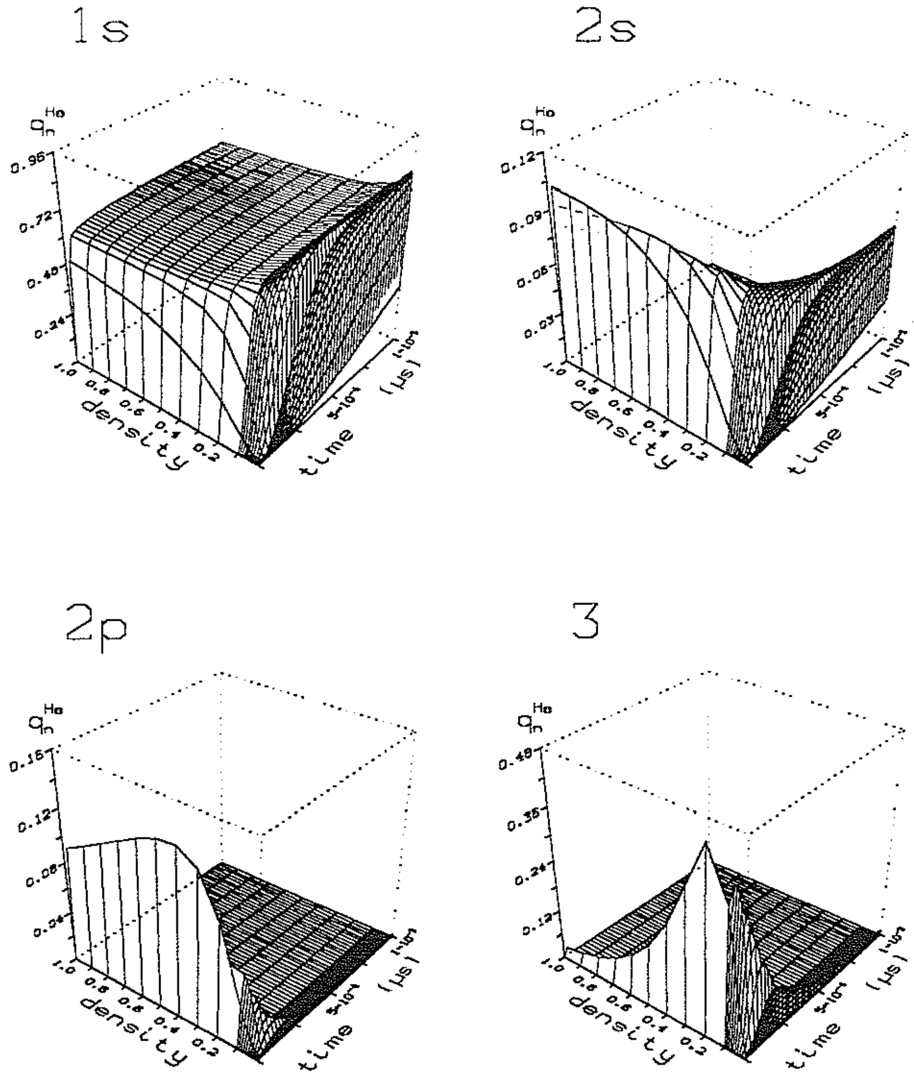

Fig.2a

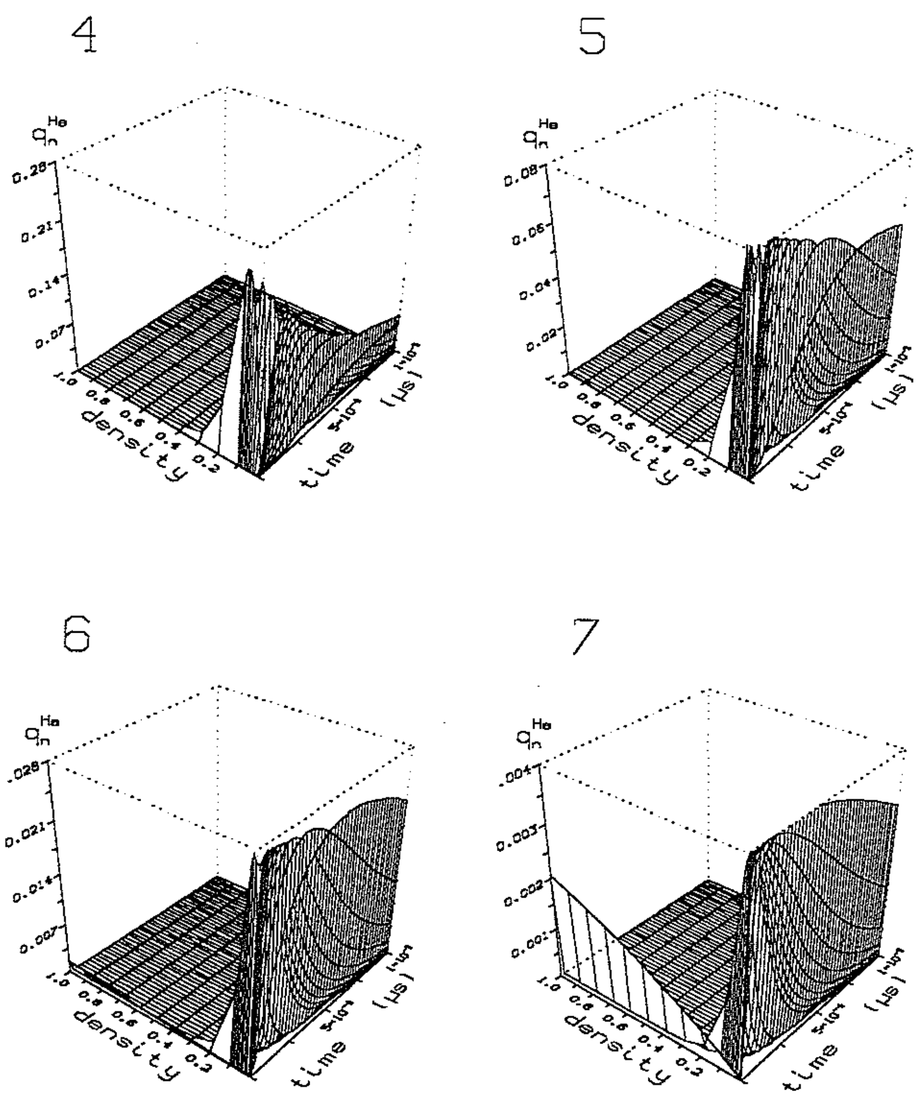

Fig.2B

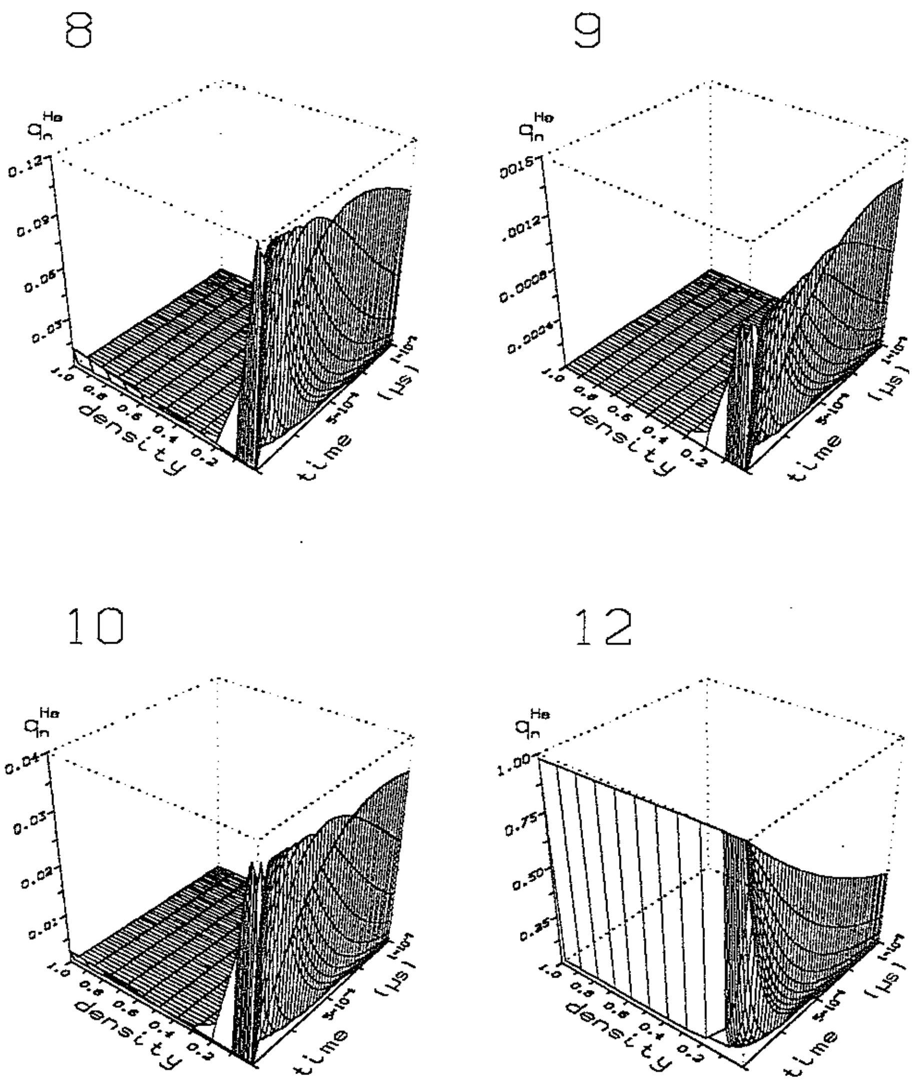

Fig.2c

Fig.2. Dependence of $q_n(t, \phi)$ for $1s$, $2s$, $2p$, $n = 3$ (a), $n = 4, 5, 6, 7$ (b) and $n = 8, 9, 10, 12$ (c) calculated for $\varepsilon = 0.04eV$ and $C_{He} = 0.05$ in $D_2 +^3 He$ mixture; Coulomb deexcitation rates were taken from [9c].

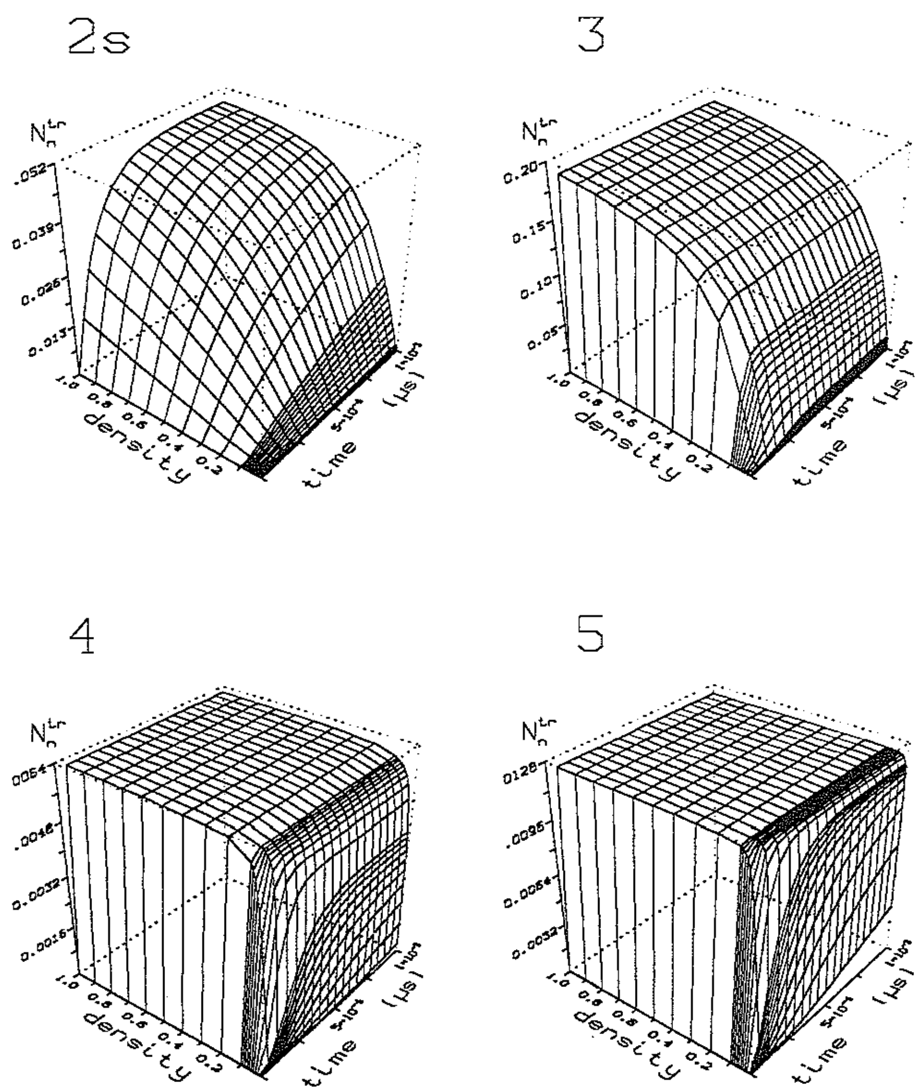

Fig.3a

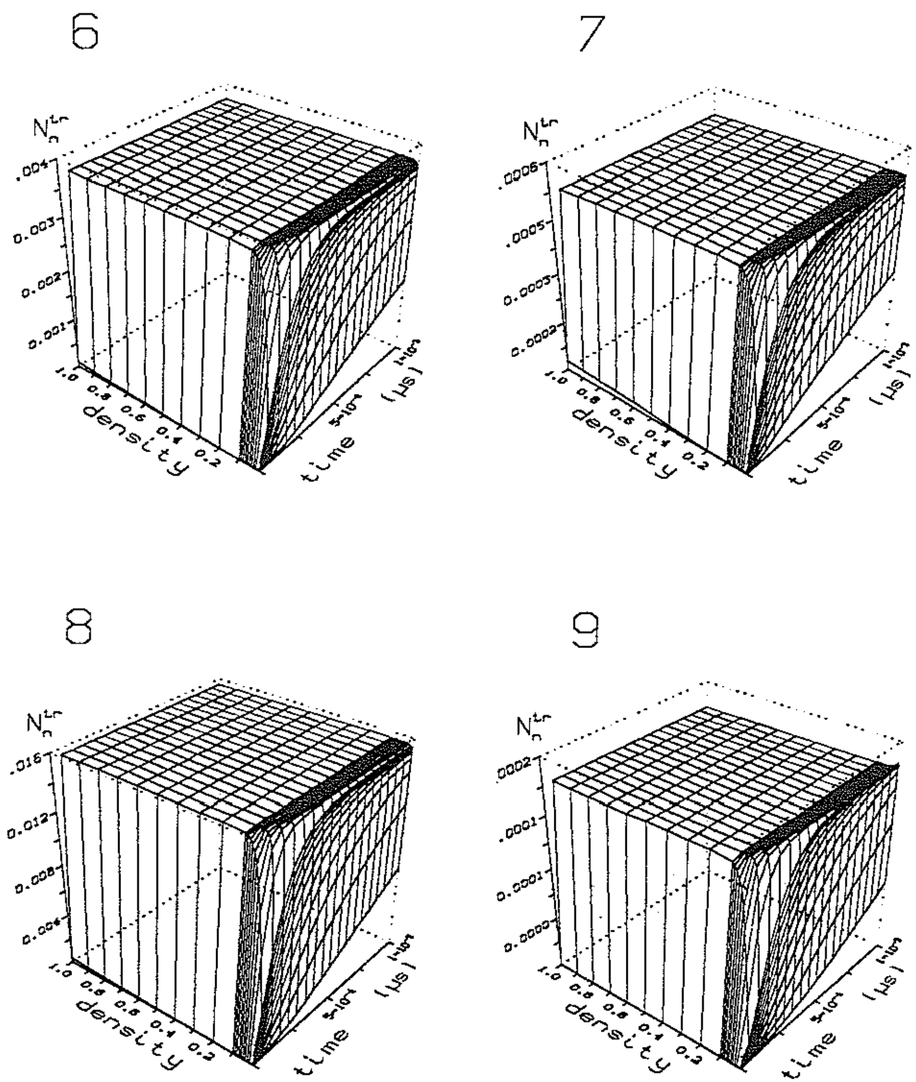

Fig.3B

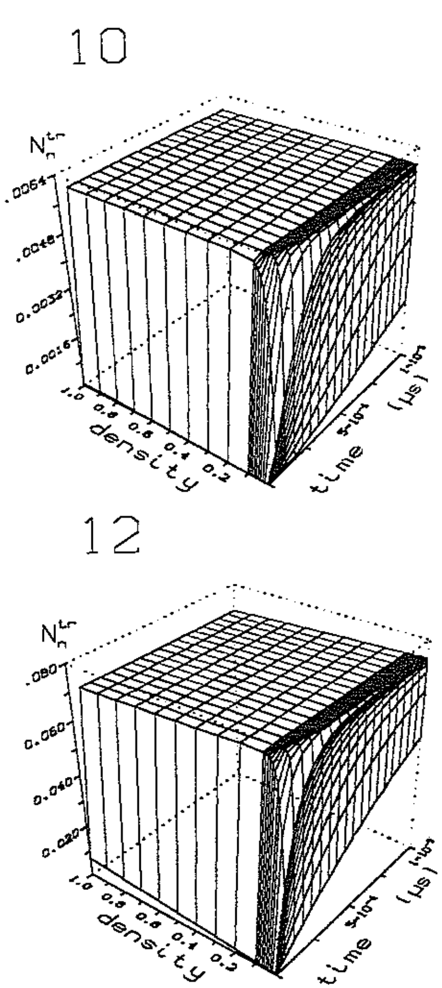

Fig.3c

Fig.3. The number of muons transferred to helium $N_n^{tr}(t,\phi)$ calculated for $\varepsilon = 0.04eV$ and $C_{He} = 0.05$ in $D_2{+}^3He$ for $2s$, $n = 3,4,5$ (a), $n = 6,7,8,9$ (b) and $n = 10,11,12$ (c). Coulomb deexcitation rates were taken from [9c].

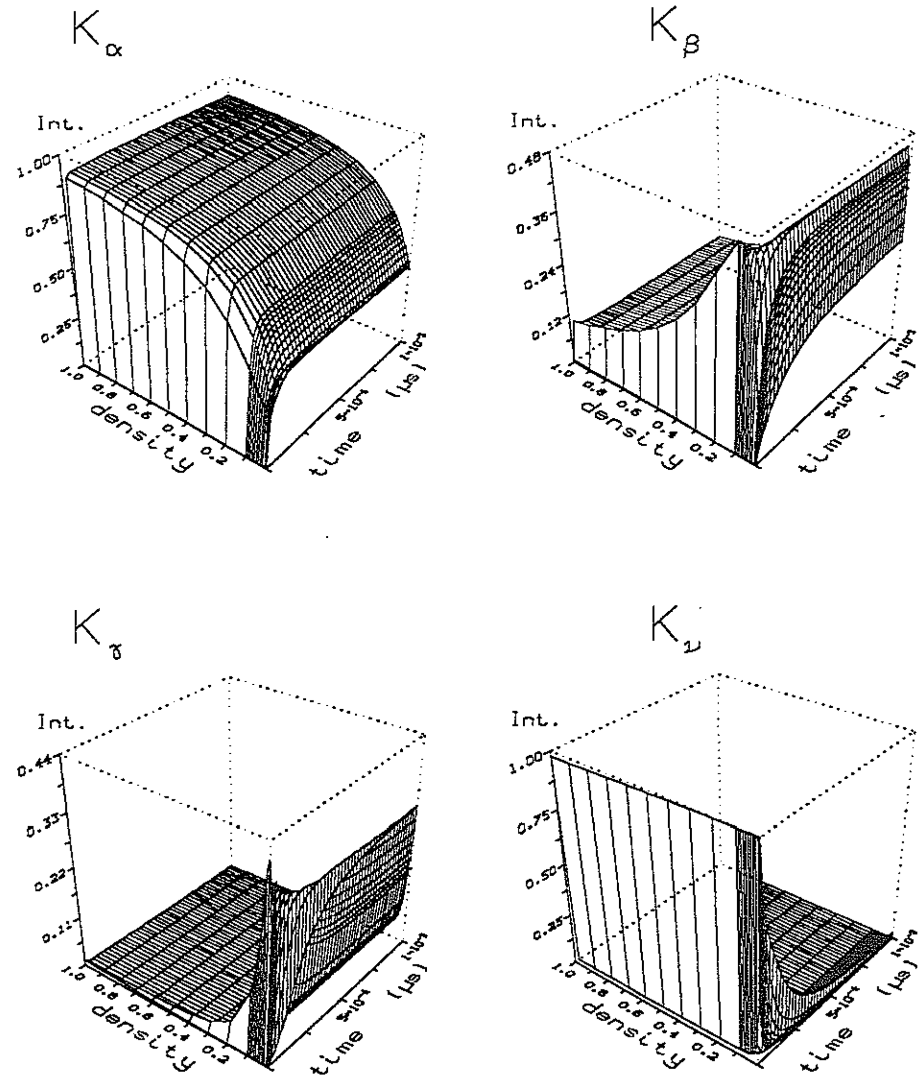

Fig.4. The ϕ and t dependence of relative intensities of K x-rays calculated for $\varepsilon = 0.04eV$ and $C_{He} = 0.05$ in $D_2 +^3 He$. Coulomb deexcitation rates were taken from [9c].

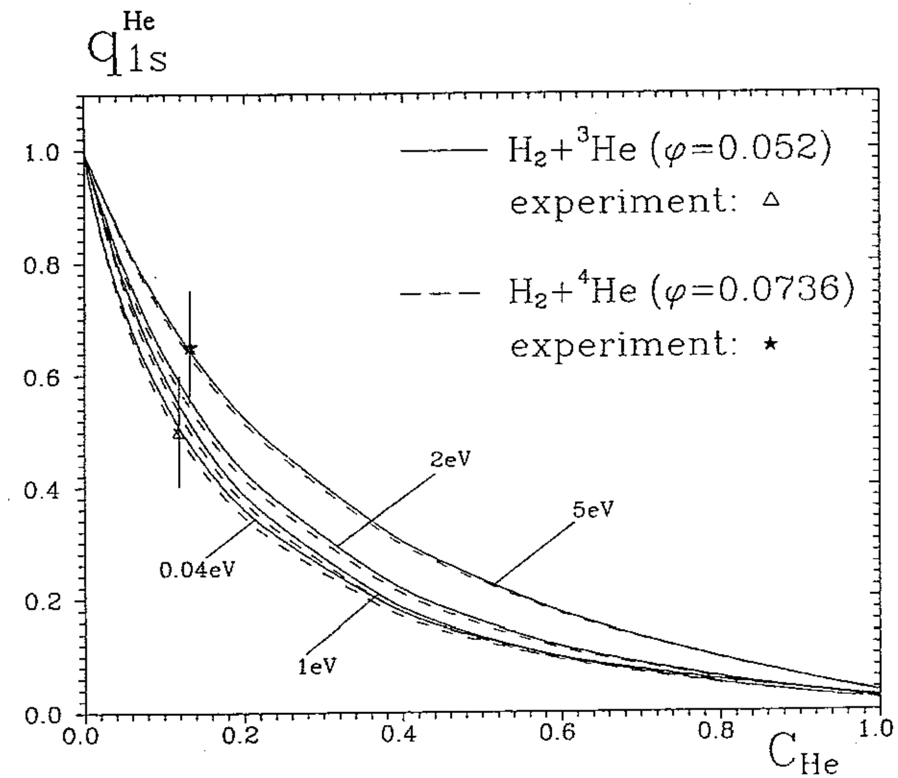

Fig.5. Comparison of theoretical $q_{1s}^{He}(C_{He})$ curves with experimental data [14] (ε is indicated on curves) obtained for Coulomb rates from [9c].

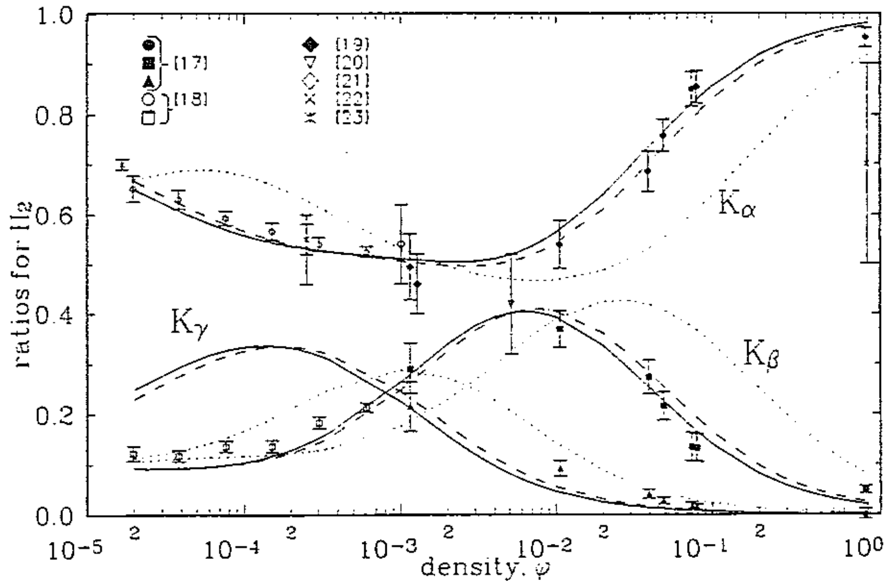

Fig.6. The ϕ dependence of relative intensities of K x-rays calculated in pure H_2 (a) and pure D_2 (b) for $\phi = 10^{-5} \div 1$ in comparison with experiment [16-24]. The Coulomb deexcitation rates were taken for

a):

$\lambda_C(3 \to 2) = 1.2 \cdot 10^{12} s^{-1}$ (solid lines)

$\lambda_C(3 \to 2) = 9.0 \cdot 10^{11} s^{-1}$ (long dashed lines)

$\lambda_C(3 \to 2) = 4.8 \cdot 10^{9} s^{-1}$ (short dashed lines)

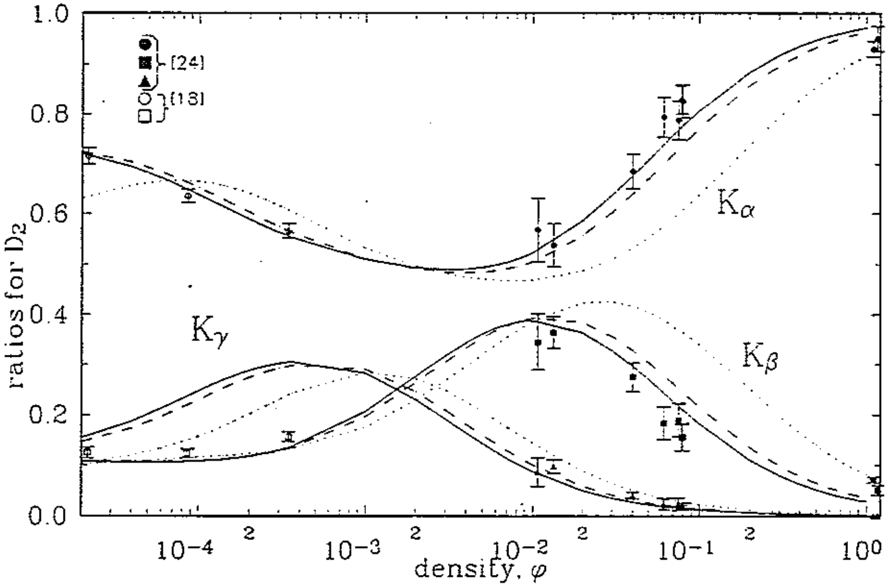

Fig.6 b):

$\lambda_C(3 \to 2) = 7.2 \cdot 10^{11} s^{-1}$ (solid lines)

$\lambda_C(3 \to 2) = 4.8 \cdot 10^{11} s^{-1}$ (long dashed lines)

$\lambda_C(3 \to 2) = 4.8 \cdot 10^{9} s^{-1}$ (short dashed lines)

Acknowledgment

We are very grateful to V.P.Popov for cooperation in obtaining of some partial Stark transition rates and A.Gula and E.A.Solov'ev for valuable comments. We are indebted also to J.S.Cohen for sending his paper before its publication. One of us (V.B.) is indebted to RFFI for financial support by Grant No. 98-02-16460.

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Received by Publishing Department
on May 19, 1999.