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DYNAMICS OF MUONIC ATOM CASCADE IN HYDROGEN–HELIUM MIXTURES

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1 Introduction

Nuclear fusion in charge-asymmetric muonic molecules $h\mu Z$, where $h \equiv p, d, t$, and $Z \equiv {}^3He, {}^4He, {}^6Li, {}^7Li, {}^7Be...$) provides rare possibility to investigate the strong interaction at relatively low energies $\sim keV$. Results obtained may through the light on some fundamental questions of physics (charge symmetry of strong interaction and iso-invariance, the character of P- and T-invariance) and may be also of interest for the problem of the primordial nucleosynthesis of light nuclei in the early Universe [1]. Energy region realized in muonic molecules is not accessible now in accelerator experiments due to small intensity of particle beams and low fusion cross sections ($\sim 10^{-36} \div 10^{-42}\ cm^2$) expected at this energy region.

The intensive experimental research of nuclear fusion in deuterium-helium muonic molecule [1] is realized now at meson factories [2-5]. However, for correct interpretation of the obtained experimental results it is necessary to have detailed information about all processes occurring during the short time of deexcitation of the muonic atom and for the formation of the muonic molecule. These processes are: deexcitation of muonic hydrogen via radiative transition [6] and Auger transition [7-9], Stark mixing [7], Coulomb deexcitation [10,11], muon transfer from excited muonic hydrogen to other nuclei [12-16], and elastic collisions [17] responsible for thermalization of muonic hydrogen. Acceleration of muonic hydrogen during the cascade is mainly due to Auger transitions and Coulomb deexcitation.

The scheme of cascade for $d\mu$ atoms in $D_2 + He$ mixture is presented in Fig.1 as an example (the same scheme of deexcitation is supposed for muonic protium and tritium). It is practically impossible to realize experimentally time-

[1]Such system is preferred now due to a lot of theoretical and experimental papers concerning the properties of this molecule.

separation of all processes presented in Fig.1 due to their large number and short time of the cascade ($\leq 10^{-11}s$ at the liquid hydrogen density, LHD). However it is possible to separate the formation of the muonic hydrogen and the muon transfer from hydrogen to helium in excited states.

In this paper theoretical results for the probability of the deexcitation of $p\mu$ and $d\mu$ atoms to the ground state (the so called q_{1s}^{He} parameter)[2] in $H_2 +^{3,4} He$ and $D_2 +^{3,4} He$ mixture, respectively, are presented and compared with the new experimental ones obtained for $H_2 +^4 He$ mixture. The probability for Coulomb muon capture[3] by hydrogen in different hydrogen-helium isotopic mixtures is also presented. Results for q_{1s}^{He} have been obtained using new theoretical data for muon transfer from excited states [16]. Auger transitions induced by collisions of muonic hydrogen with helium atoms are also used in calculations.

2 Method of consideration

Experimental investigation of the nuclear fusion in charge asymmetric muonic molecules is realized now for reactions

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

$$d\mu^4He \xrightarrow{\lambda_f} {}^6Li + \gamma(1.48MeV) + \mu. \tag{2}$$

and results presented in this paper are of special interest for these isotopic systems.

Measurement of reaction rate, λ_f, for fusion in $d\mu He$ molecule, eqs.(1,2), bases

[2]The index "He" was added to underline that hydrogen-helium isotopic mixtures are considered.

[3]It is called throughout the text as direct muon capture

on the analysis of the yield and the time-distributions of fusion products as well as the characteristic gamma-rays from the decay of $d\mu He$ molecules [4]. Because the number of fusion products and characteristic gamma quanta per one muonic molecule are needed for the analysis one has to know the number of all particles produced in fusion and the number of $d\mu He$ molecules formed in $D_2 + He$ mixture.

The number of muonic molecules is proportional to the number of $d\mu$ atoms in the ground state which is determined by the probability

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

that the muon stopped in the mixture will be captured by deuterium into an excited atomic orbit and the resulting $d\mu$ atom will reach the ground state. W_D and q_{1s}^{He} are the corresponding probabilities. Probability W is a function of the mixture density, ϕ (usually expressed in the unit of the liquid hydrogen density, LHD, $N_0 = 4.22 \cdot 10^{22} cm^{-3}$), and the helium concentration, C_{He}. It may be obtained from the analysis of experimental data using the method presented in [19]. However, experimental determination of W is very difficult because it should be measured together with fusion rate, i.e. at the same experimental conditions. Theoretical estimation of q_{1s}^{He} and W_D becomes therefore very important supposing that the scheme of deexcitation of muonic hydrogen and the corresponding reaction rates are well known. The situation, however, is still not satisfactory due to the lack of the cross sections for deexcitation processes induced by collisions of muonic hydrogen with helium atom. Nethertheles the estimations of some missing data are proposed in this paper and results for q_{1s}^{He} are given.

[4]The characteristic gamma-ray, 6.85 keV, corresponds to the transition between $2p\sigma$ and $1s\sigma$ molecular terms [18].

Let us briefly describe the processes induced by muons entering a hydrogen-helium isotopic mixture.

Muonic hydrogen atoms are formed in highly excited states ($n \approx 8 \div 16$).and n-state distribution has a maximum for $n = 14 \approx \sqrt{m_{mu}/m_e}$ [20] where m_μ and m_e are the reduced masses of the muonic and electronic hydrogen atom, respectively. The probability of direct muon capture by deuterium W_D can be expressed as

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

where C_D is deuterium concentration ($C_{He} + C_D = 1$) and A is the ratio of the capture rates for helium and deuterium: $A = 1.7 \pm 0.2$ [19]. Muonic hydrogen atoms undergo fast deexcitation to states with $n = 12$ due to target molecules dissociation and Auger transitions. So we suppose in calculations that the cascade starts at $n = 12$.

For $n \geq 10$ deexcitation of muonic deuterium is dominated by target molecule dissociation in collision processes [7] (below $D_2 + He$ mixture is taken as an example)

$$(d\mu)_n + D_2 \rightarrow (d\mu)_{n'} + D + D, \tag{5}$$

where transition energy matches the energy of hydrogen molecule dissociation, $\varepsilon_{dis} \approx 4.7$ eV. Corresponding cross sections have been approximated (following [7]) by the geometrical ones.

For $4 \leq n \leq 10$ deexcitation due to ionisation of hydrogen molecules [7]

$$(d\mu)_n + D_2 \rightarrow (d\mu)_{n'} + D_2^+ + e, \tag{6}$$

or helium atoms

$$(d\mu)_n + He \rightarrow (d\mu)_{n'} + He^+ + e \tag{7}$$

dominates (outher Auger effect), where transitions with $n - n' = 1$ are preferred[5]. Collisions with surrounding molecules and atoms lead to fast deexcitation to the states with $n \approx 4 \div 5$ during the time $\sim 10^{-12}\phi^{-1}s$. Below $n < 6$, radiative deexcitation dominates and $1s$ state is reached after about $10^{-11}s$. The corresponding radiative rates were obtained according to [6] and are presented in Table 1.

An important role in cascade plays also Coulomb deexcitation [10,11]

$$(d\mu)_n + d \rightarrow (d\mu)_{n-1} + d \tag{8}$$

and

$$(d\mu)_n + He \rightarrow (d\mu)_{n-1} + He. \tag{9}$$

For $n \geq 4$ the corresponding cross sections for collision with deuterium nucleus are nearly compared with those for molecule dissociation.

As it was shown in refs. [21] about $6\% \div 15\%$ of muonic atoms deexcite via $2s$ state from which radiative transition to the $1s$ state is forbidden [6]. Therefore, collision induced $2s \rightarrow 2p$ transition for collision energies, ε, greater than the Lamb-shift ($\Delta E_L \approx 0.2$ eV), and subsequent $2p \rightarrow 1s$ radiative transition became important in cascade scheme [22]. For $\varepsilon < \Delta E_L$, $2s \rightarrow 2p \rightarrow 1s$ transitions due to Stark mixing of $2s$ and $2p$ states may occur [7].

There is no theoretical data for deexcitation processes described above induced by collisions with helium atom. The corresponding Auger rates were approximated by $2\lambda_A$, where λ_A were calculated according to formulae presented in [7] for helium ionisation energy, $I_{He} = 24.68$ eV, instead the one for hydrogen molecule. They are presented in Table 1 (in parenthesis) for muonic deuterium as an example together with Auger rates for collision of muonic deuterium with

[5]The probability of Auger transitions is proportional to $(\Delta E)^{-1/2}$.

[6]The Lamb-shift in muonic hydrogen atoms is caused mainly by e^+e^- vacuum polarisation which shifts $2s$ level below $2p$.

deuterium molecule. Reaction rates for Coulomb deexcitation and transitions between $2s$ and $2p$ (including induced $2s \rightarrow 2p \rightarrow 1s$ transitions) were supposed to be the same as those for collisions of muonic deuterium with tritium and were taken from [10] and [11,22], respectively.

Deexcitation processes compete with muon transfer to helium nucleus

$$(d\mu)_n + He \rightarrow (He\mu)_n + d. \tag{10}$$

Corresponding reaction rates were calculated in [16] for the principal quantum number $n \leq 5$. Because there is no theoretical data for the muon transfer to helium from $n > 5$ the corresponding transfer rates were supposed to be the same as the transfer rate for $n = 5$.

The quantity q_{1s}^{He} (ground state population of muonic hydrogen) depends on ϕ, collision energy ε, C_{He} and the competition between deexcitation of muonic hydrogen and muon transfer to He nuclei.

Theoretical results for q_{1s}^{He} calculated for $H_2 +^{3,4}He$ and $D_2 +^{3,4}He$ mixtures presented in this paper were obtained in the so called cascade model which assumes constant kinetic energy ($1 \div 5eV$) of a muonic atom during the cascade. The method bases on solution of the system of the coupled linear differential equations corresponding to the scheme of the cascade prsented in Fig.1 with the initial population of the states: $q_{12}^{He} = 1$ and $q_{n<12} = 0$. This model applied in [11] for calculation of q_{1s} for $d\mu$ atoms in $D_2 + T_2$ mixture gave results very close to those obtained by Monte-Carlo method that includes acceleration and thermalization of muonic atoms during the cascade [23].

3 Results

Figs 2a-2c show the calculated dependence of q_{1s}^{He} (for $H_2 +^4He$, $D_2 +^3He$ and $D_2 +^4He$ mixtures, respectively) upon the relative helium concentration C_{He}

for different values of the mixture density ϕ and collision energies $\varepsilon = 0.04$ eV (dashed lines), and 5 eV (solid lines). All radiative and Auger transition rates presented in Table 1 have been included. Fig. 3a obtained for $\varepsilon = 0.04$ eV and $5eV$ illustrates the influence of muon transfer from $n > 5$. As follows from Fig. 3b the contribution of secondary Auger and radiative transitions (presented in Table 1 but not presented in Fig.1) is very important especially at large helium concentrations. It is due to the fact that Auger transitions, $n \rightarrow n - k, k = 1, 2, 3$, induced by collisions of muonic hydrogen with helium atoms are energetically disallowed (see Table 1).

Fig.4 shows the energy dependence of q_{1s}^{He} for $\phi = 0.1$ and $C_{He} = 0.4$ as an example for all considered mixtures. The character of energy dependence does not practically depend on these parameters. It should be noted, however, that unlike the deuterium-tritium mixture [11,12] energy dependence of q_{1s}^{He} for deuterium-helium mixture is rather weak. The analogous comparison of q_{1s}^{He} in $H_2 +^4He$ mixture with $H_2 + D_2$ mixtures was given in [24]. As it was already indicated in [14] the weak energy dependence of q_{1s}^{He} is due to relatively small rate of the muon transfer to helium from the metastable $2s$-state [13, 15, 16]. It is about an order of magnitude smaller than the rate for muon transfer to tritium [11]. At the same time reaction rate for deexcitation of $2s$-state (due to $2s \rightarrow 2p$ and the subsequent $2p \rightarrow 1s$ transition) has a strong energy dependence due to the presence of $2s - 2p$ Lamb-shift threshold, ΔE_L. Therefore, the increase of q_{1s}^{He} for $\varepsilon > 0.2eV$ is much less pronounced than the increase of q_{1s} in $D_2 + T_2$-mixture.

The decrease of q_{1s}^{He} for $\varepsilon < 0.2eV$ (see Fig. 4) is mainly due to the rise of muon transfer rates in this energy region [16]. Additionally, increasing with energy $2p \rightarrow 2s$ transition rate [22] enhances the population of $2s$ state. It results in faster muon transfer to helium from this state and additional decrease of q_{1s}^{He}.

For collision energy $\varepsilon > 0.2eV$ $2s \rightarrow 2p$ transition is switched on and $2s$ state deexcites to the ground state due to $2s \rightarrow 2p$ transition and the subsequent $2p \rightarrow 1s$ radiative transition. Increasing with energy $2s \rightarrow 2p$ transition rate and decreasing for $\varepsilon > 0.5eV$ muon transfer rates lead to monotonical increase of q_{1s}^{He}.

The values of q_{1s}^{He} for H_2+^4He mixture in $0 \div 1eV$ energy range (see Fig.2a) are some smaller than those presented in Fig.2 of [14]. It is because cascade and transfer processes have been considered in the present paper for $n \leq 12$ (see Fig.1 and Table 1) whereas such processes were considered in [14] for $n \leq 5$.

The dependence of W on C_{He} for different ϕ and $\varepsilon = 0.04eV$ and $5eV$ for $H_2 +^4 He$ and $D_2 +^3 He$ mixtures is shown in Fig. 5a and 5b, respectively. Some of these results are presented also in Table 2 together with comparison of calculated values of q_{1s}^{He} and W with the experimental ones [19, 25] obtained for $H_2 +^4 He$ mixture.

Fig. 6 presents the comparison of the experimental values of $q_{1s}^{^4He}$ [19,25] with theoretical ones calculated for the same target densities and collision energy ε indicated on curves. As seen, the agreement between experimental and theoretical data is received for collision energy $\varepsilon > 0.04eV$. As follows from this the average energy of muonic hydrogen atoms, corresponding to their real energy distribution in excited states with $n \approx 2 \div 4$, is much greater than the thermal one. This circumstance results in greater probability of the Stark $2s \rightarrow 2p$ and induced $2s \rightarrow 2p \rightarrow 1s$ transitions.

One can conclude that an agreement between experimental and theoretical data is possible for indicated $H_2 +^4 He$ mixture if theoretical q_{1s}^{He} values are calculated for high collision energy $\varepsilon \sim 2 \div 5eV$ of excited muonic hydrogen and He atom (see Table 2 and Fig.6).

In the conclusion, we can argue that comparison of experimental data of W (and correspondently q_{1s}^{He}) obtained for different ϕ and C_{He} with corresponding theoretical ones could allow one to verify the cascade scheme and to obtain transfer rates from excited muonic hydrogen to helium using χ^2 analysis.

Acknowledgment

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Table 1

transition	Auger rates [$10^{10} s^{-1}$]	radiative rates [$10^{10} s^{-1}$]
2p → 1s	0.508 (1.017)	12.26
3p → 1s	0.075 (0.150)	3.273
3p → 2s	6.636 (13.44)	0.439
3d → 2p	19.11 (38.71)	1.265
3s → 2p	1.866 (3.780)	0.124
4p → 1s	0.025 (0.051)	1.334
4p → 2s	1.001 (2.020)	0.189
4d → 2p	2.135 (4.310)	0.404
4s → 2p	0.267 (0.539)	0.051
4 → 3	104.0 (215.7)	0.176
5p → 1s	0.012 (0.235)	0.673
5p → 2s	0.345 (0.695)	0.097
5d → 2p	0.656 (1.324)	0.184
5s → 2p	0.090 (0.181)	0.025
5 → 3	6.750 (13.84)	0.043
5 → 4	457.1 (989.9)	0.053
6p → 1s	0.006 (0.013)	0.386
6p → 2s	0.163 (0.329)	0.055
6d → 2p	0.294 (0.593)	0.101
6s → 2p	0.042 (0.085)	0.014
6 → 3	1.372 (2.802)	0.015
6 → 4	28.85 (60.73)	0.015
6 → 5	1437 (3327)	0.020
7p → 1s	0.004 (0.008)	0.242
7p → 2s	0.092 (0.185)	0.035
7d → 2p	0.160 (0.322)	0.061
7s → 2p	0.023 (0.047)	0.009
7 → 3	0.440 (0.898)	0.007
7 → 4	5.817 (12.13)	0.006
7 → 5	89.08 (195.2)	0.006
7 → 6	3620 (0.000)	0.009
8p → 1s	0.003 (0.005)	0.162
8p → 2s	0.057 (0.115)	0.024
8d → 2p	0.097 (0.196)	0.040
8s → 2p	0.014 (0.029)	0.006
8 → 3	0.181 (0.368)	0.003
8 → 4	1.871 (3.887)	0.003
8 → 5	17.79 (38.29)	0.003
8 → 6	223.2 (517.0)	0.003
8 → 7	0.000 (0.000)	0.004
9p → 1s	0.002 (0.004)	0.113
9p → 2s	0.038 (0.077)	0.017
9d → 2p	0.064 (0.129)	0.028
9s → 2p	0.010 (0.019)	0.004
9 → 3	0.087 (0.176)	0.002
9 → 4	0.774 (1.604)	0.002
9 → 5	5.709 (12.18)	0.001
9 → 6	44.25 (99.42)	0.001
9 → 7	481.4 (0.000)	0.002
9 → 8	0.000 (0.000)	0.002
10p → 1s	0.001 (0.003)	0.082
10p → 2s	0.027 (0.054)	0.012
10d → 2p	0.045 (0.090)	0.020
10s → 2p	0.007 (0.014)	0.003
10 → 3	0.046 (0.094)	0.001
10 → 4	0.375 (0.775)	0.001
10 → 5	2.365 (5.020)	0.001
10 → 6	14.15 (31.30)	0.001
10 → 7	95.17 (225.6)	0.001
10 → 8	0.000 (0.000)	0.001
10 → 9	0.000 (0.000)	0.001
11p → 1s	0.001 (0.002)	0.062
11p → 2s	0.020 (0.040)	0.0001
11d → 2p	0.033 (0.065)	0.015
11s → 2p	0.005 (0.010)	0.002
11 → 3	0.027 (0.054)	0.001
11 → 4	0.202 (0.417)	0.001
11 → 5	1.150 (2.431)	0.0004
11 → 6	5.858 (12.84)	0.0004
11 → 7	30.35 (70.32)	0.0004
11 → 8	183.4 (0.000)	0.001
11 → 9	0.000 (0.000)	0.001
11 → 10	0.000 (0.000)	0.001
12p → 1s	0.001 (0.001)	0.048
12p → 2s	0.015 (0.030)	0.007
12d → 2p	0.024 (0.049)	0.011
12s → 2p	0.004 (0.008)	0.002
12 → 3	0.016 (0.033)	0.004
12 → 4	0.118 (0.243)	0.0003
12 → 5	0.623 (1.314)	0.0002
12 → 6	2.850 (6.213)	0.0003
12 → 7	12.55 (28.68)	0.0002
12 → 8	58.44 (0.000)	0.0003
12 → 9	0.000 (0.000)	0.0003
12 → 10	0.000 (0.000)	0.0003
12 → 11	0.000 (0.000)	0.001

Table 1. Reaction rates for radiative deexcitation of muonic deuterium atom and Auger transitions induced by collision of muonic deuterium with deuterium molecule. Auger rates for deexcitation of muonic deuterium in collision with helium atom are presented in parenthesis.

Table 2. The comparison of experimental and calculated values of W and q_{1s}^{He} for $H_2 + {}^4He$ at different ϕ and C_{He}. Experimental errors are indicated in parenthesis. Theoretical data were calculated for $\varepsilon = 0.04eV$ and $5eV$ (in square brackets).

Table 2

	experiment ($H_2 + {}^4He$)				theory ($H_2 + {}^4He$)	
	ϕ	$C_{^4He}$	$q_{1s}^{^4He}$	W	$q_{1s}^{^4He}$	W
1	0.031	0.048	0.94(8)	0.87(3)	0.77 [0.87]	0.71 [0.80]
2	0.032	0.099	0.82(7)	0.70(4)	0.61 [0.75]	0.52 [0.63]
3	0.023	0.160	0.66(5)	0.50(2)	0.51 [0.66]	0.38 [0.50]
4	0.038	0.225	0.49(8)	0.33(5)	0.34 [0.53]	0.25 [0.35]
5	0.027	0.275	0.46(6)	0.28(3)	0.34 [0.49]	0.21 [0.30]
6	0.035	0.315	0.45(5)	0.25(2)	0.28 [0.42]	0.16 [0.24]
7	0.033	0.410	0.29(5)	0.13(2)	0.21 [0.34]	0.10 [0.16]
8	0.045	0.470	0.32(6)	0.12(2)	0.16 [0.27]	0.06 [0.11]

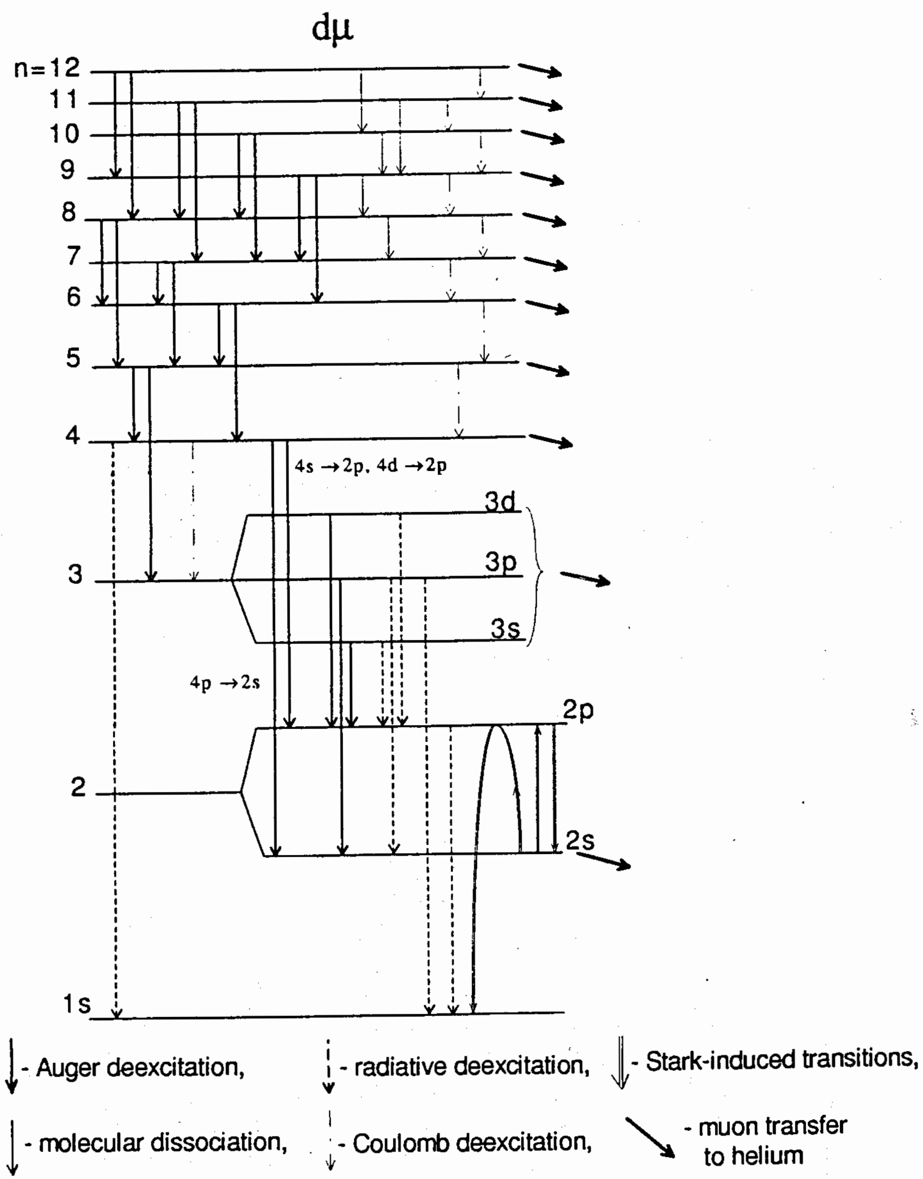


Fig.1. Scheme of muonic atom cascade for $d\mu$ atom in $D_2 + He$ mixture. Only main radiative and Auger transitions are indicated.

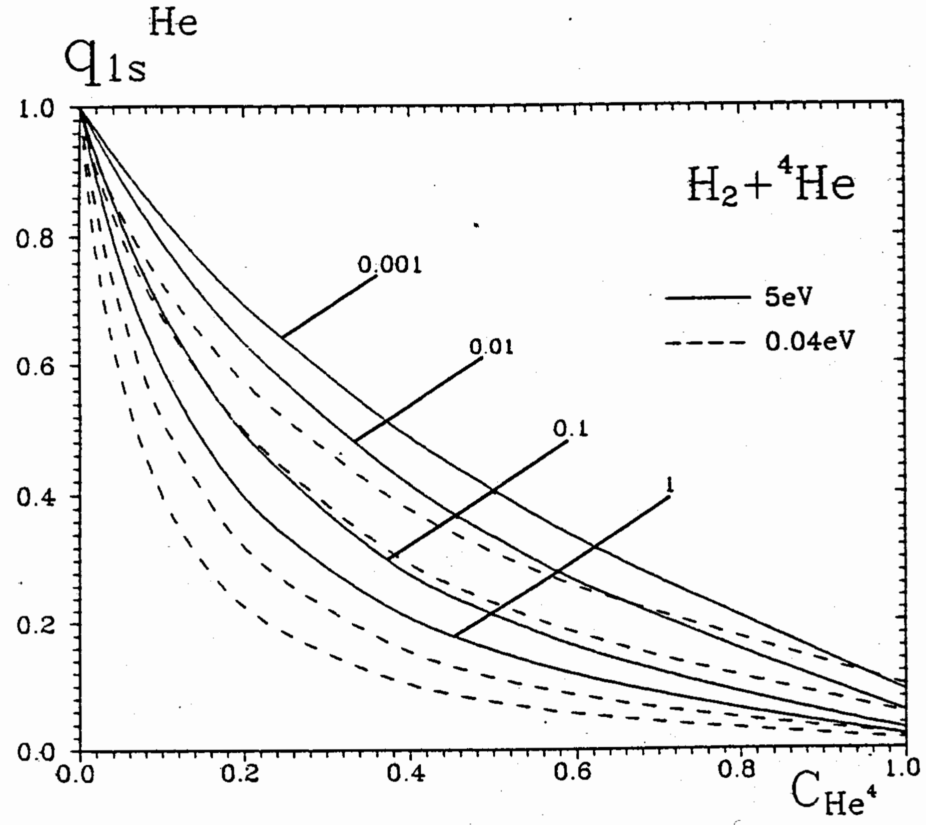
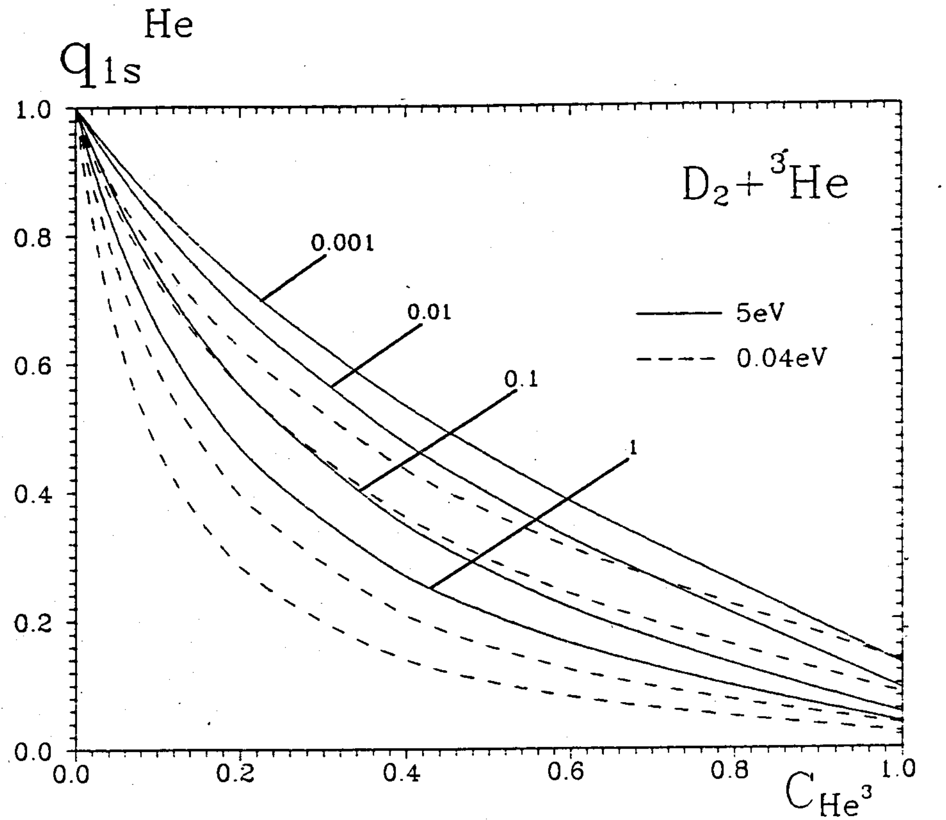


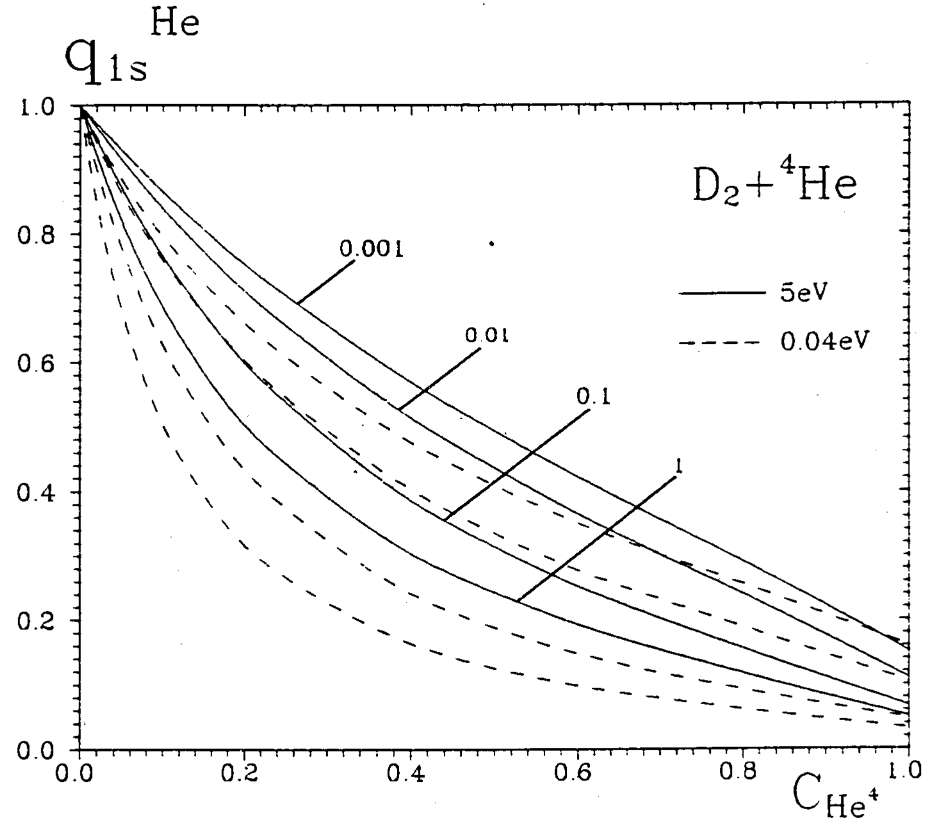
Fig.2a

Fig.2. The dependence of q_{1s}^{He} $(n \leq 12)$ on $C_{^4He}$ for $H_2 + {}^4He$ (a), $D_2 + {}^3He$ (b) and $D_2 + {}^4He$ (c) mixtures obtained for different mixture densities and different collision energies. The sequence of dashed lines is the same as solid ones.



q_{1s}^{He}
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
C_{He^3}
$D_2+{}^3He$
0.001
0.01
0.1
1
5eV
0.04eV

Fig.2b



q_{1s}^{He}
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
C_{He^4}
$D_2+{}^4He$
0.001
0.01
0.1
1
5eV
0.04eV

Fig.2c

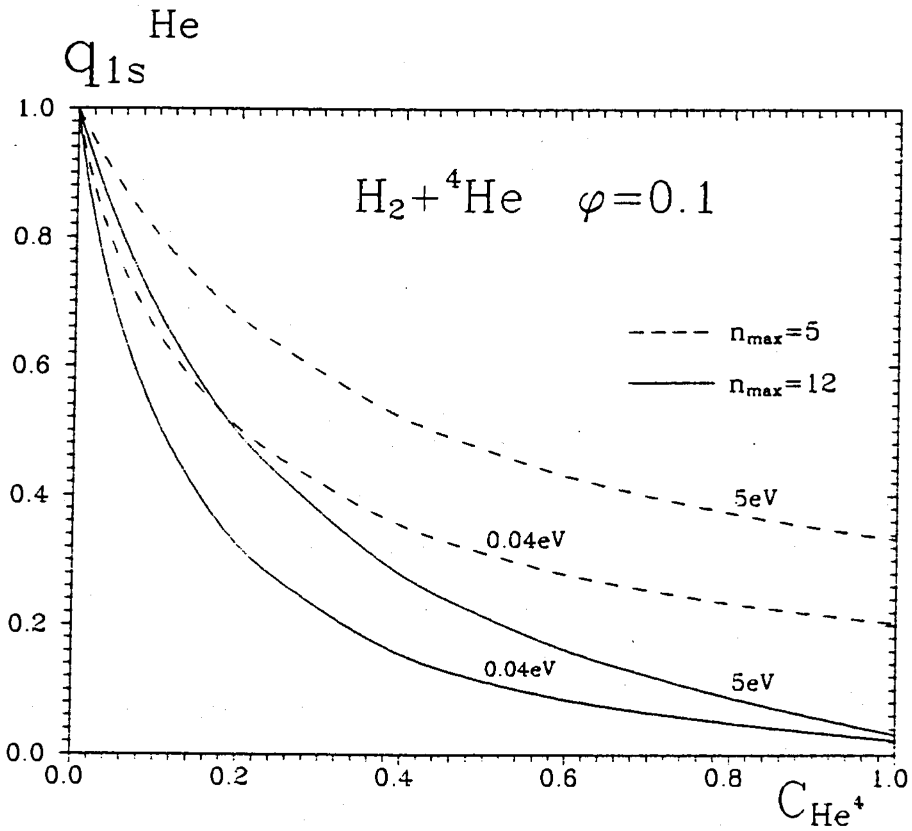


Fig.3a

Fig.3. The comparison of q_{1s} for $H_2 +^4 He$ mixture for:

a) $\phi = 0.1$ and $C_{He} = 0.4$ calculated for $n \leq 12$ and $n \leq 5$ at $\varepsilon = 0.04eV$ and $5eV$;

b) $n \leq 12$ and $\phi = 0.01$. Results were obtained for transitions presented in Table 1 (solid lines) and in Fig.1 (dotted lines). Collision energies, ε, are indicated on curves.

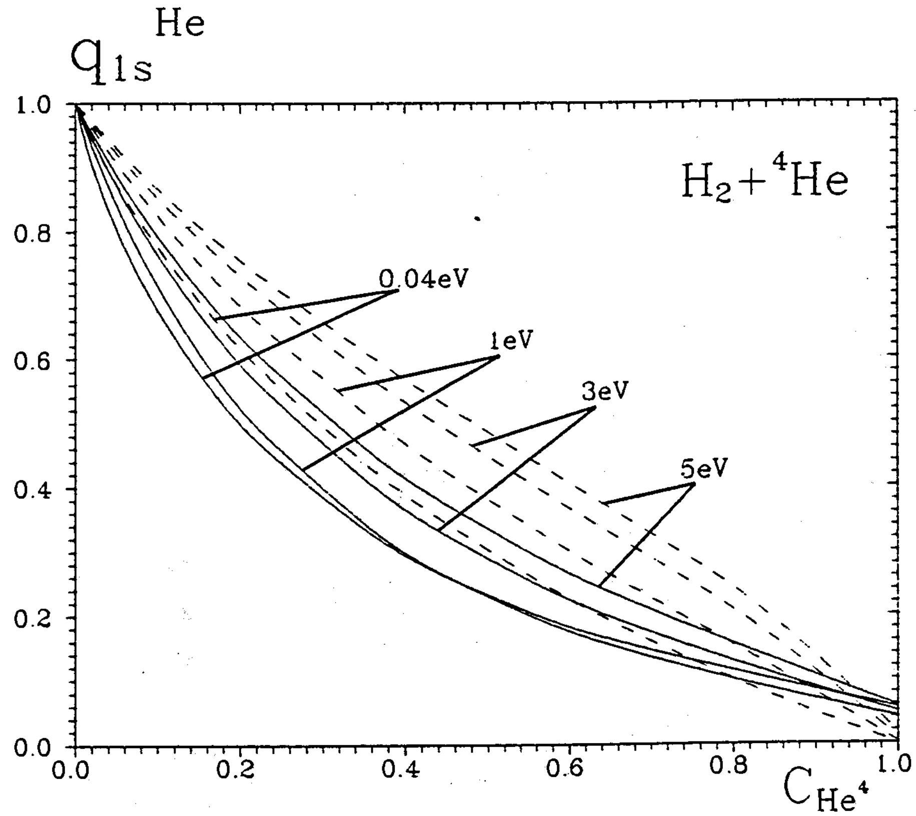


Fig.3b

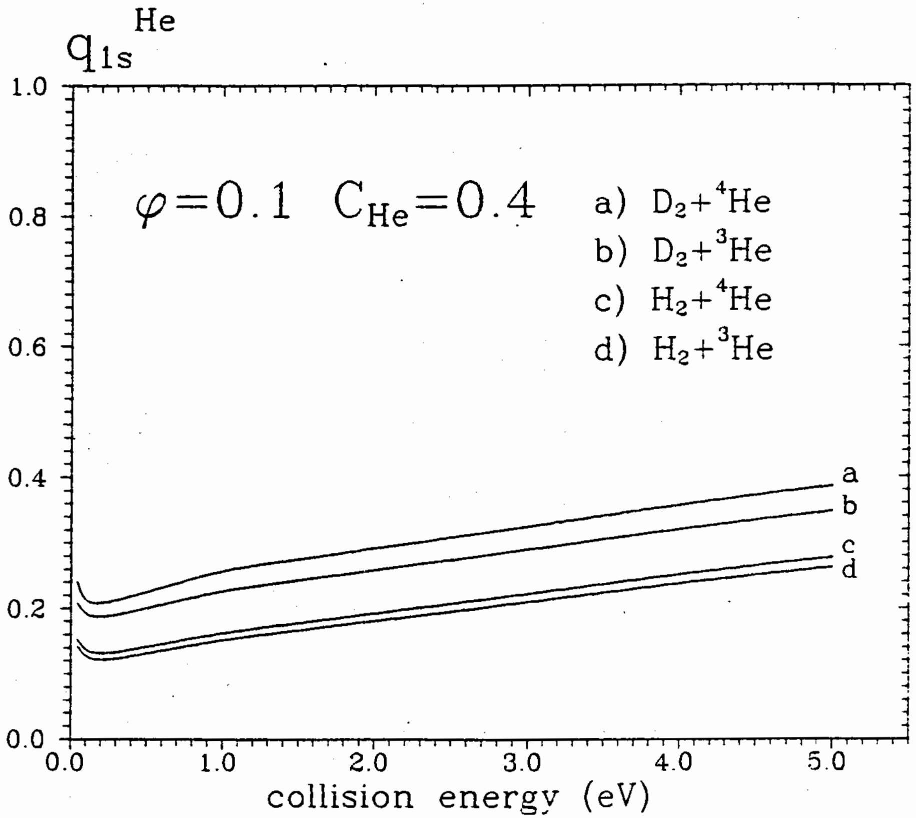


Fig.4

Fig.4. Energy dependence of q_{1s} obtained for $\phi = 0.1$, $C_{He} = 0.4$ and different isotopic mixtures.

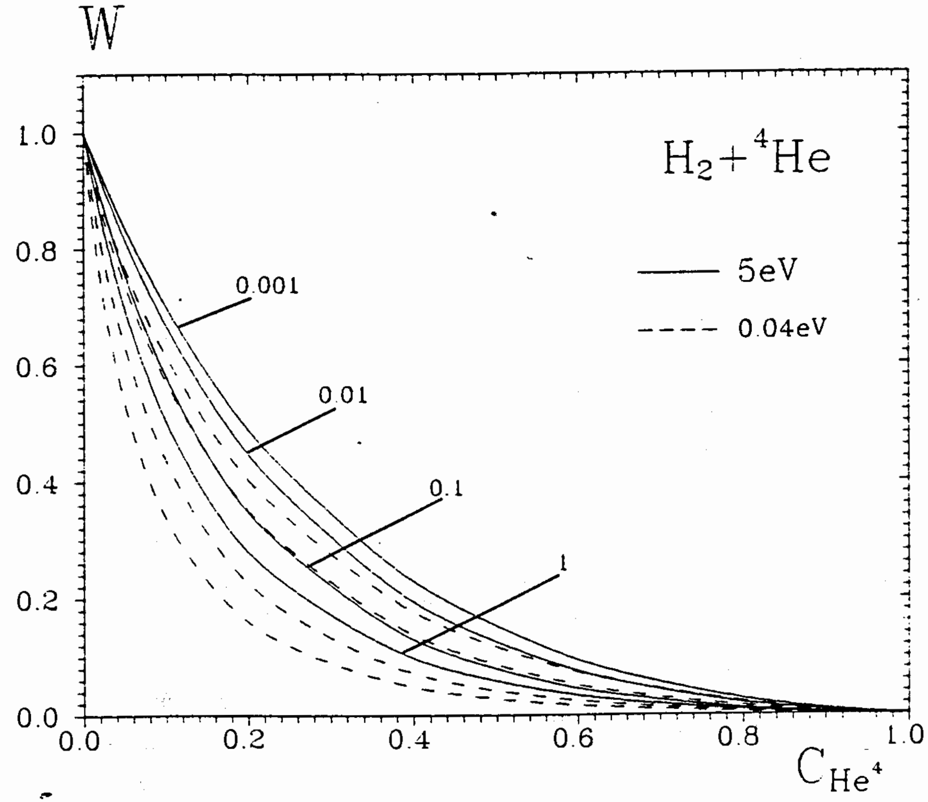


Fig.5a

Fig.5. The dependence of W on C_{He} for $H_2 +{}^4He$ (a) and $D_2 +{}^3He$ (b) mixture for ϕ and ε indicated on curves.

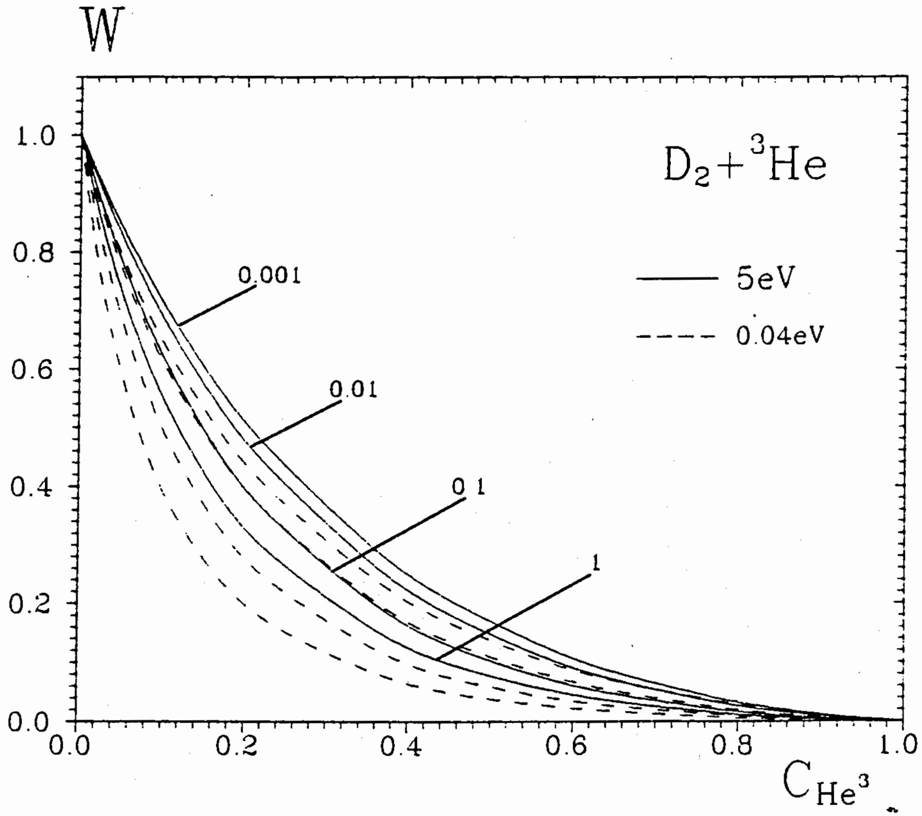


Fig.5b

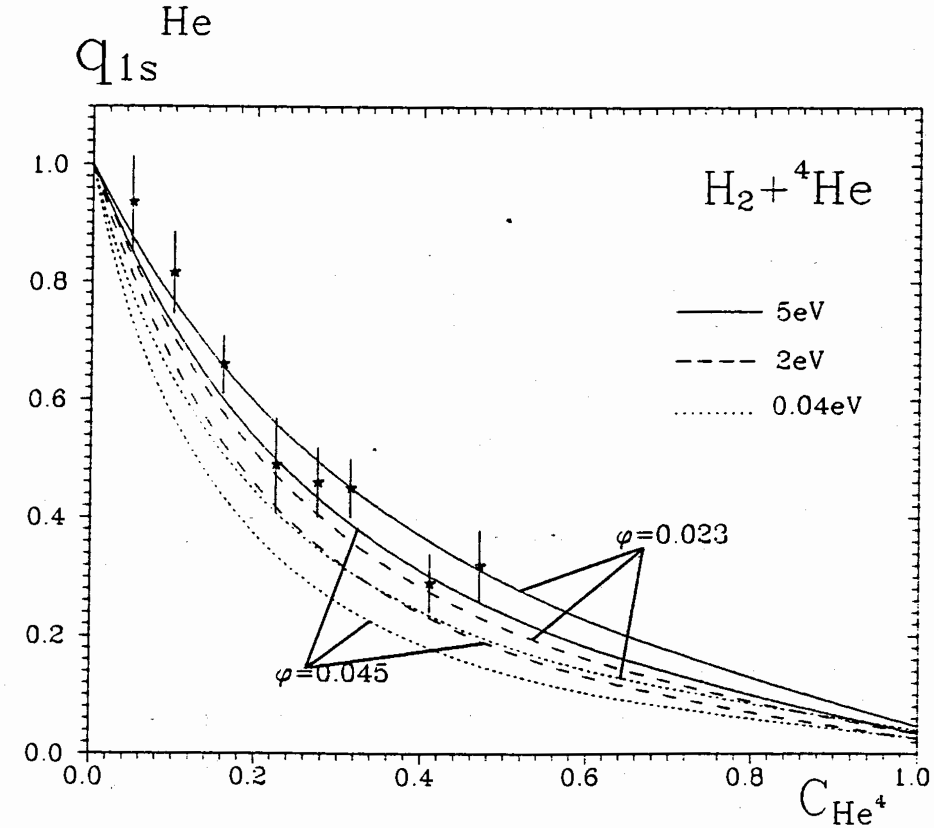


Fig.6

Fig.6. The comparison of the calculated q_{1s}^{He} for $H_2+{}^4He$ mixture with the experimental data.

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Быстрицкий В.М., Чаплински В., Попов Н.П. E15-98-234

Динамика каскада мюонного атома в водород-гелиевых смесях

Рассмотрено девозбуждение мю-атомов протия и дейтерия в смесях изотопов водорода и гелия. Предложен метод экспериментального определения вероятностей прямого атомного захвата мюонов изотопами водорода, а также скоростей перехода мюонов из возбужденных состояний мюонных атомов к ядрам He. Проводится сравнение вычисленных значений заселенности основного состояния мюонных атомов водорода q_{1s}^{He} с существующими экспериментальными данными. Расчетные значения q_{1s}^{He}, полученные для смесей $D_2 + {}^{3,4}\mathrm{He}$, необходимы также для корректной интерпретации результатов экспериментов по изучению реакций ядерного синтеза в $d\mu{}^{3,4}\mathrm{He}$-комплексах.

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Dynamics of Muonic Atom Cascade in Hydrogen–Helium Mixtures

The deexcitation of excited muonic protium and deuterium in the mixture of hydrogen and helium isotopes is considered. Method. of experimental determination of probability of direct atomic muon capture by hydrogen and muon transfer rates from excited muonic hydrogen to hemium is proposed. Theoretical results for the population of the muonic atoms in the ground state, q_{1s}^{He}, are compared with the existing experimental data. Results obtained for $D_2 + {}^{3,4}\mathrm{He}$ mixtures are of interest for investigation of nuclear fusion in $d\mu{}^{3,4}\mathrm{He}$ muonic molecules.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

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