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ON MEASUREMENT OF CROSS SECTIONS FOR SCATTERING OF $p\mu$ - AND $d\mu$ -ATOMS IN HYDROGEN AND DEUTERIUM

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To know cross sections for scattering of $p\mu$-, $d\mu$- and $t\mu$-atoms by nuclei, atoms and molecules of hydrogen isotopes is necessary not only for checking the solution algorithm for the problem of three bodies interacting by the Coulomb law but also for correct general description of the muon catalyzed fusion kinetics in nuclear fusion reactions. Besides, the knowledge of these cross sections is necessary for correct interpretation of experiments on measurement of the rate of nuclear capture of a muon by a proton, deuteron or triton, which are carried out to determine weak interaction constants. It is caused by the fact that by the moment of nuclear capture of a muon the population of levels of hyperfine structure of the ground state of $p\mu$-, $d\mu$- and $t\mu$ atoms may change because of the above scattering processes (the rate of nuclear capture of muons considerably depends on the spin state of hydrogen mu-atoms) [1], [2]. The method of measurement of scattering cross sections for muonic atoms of hydrogen isotopes is based on the relation between their diffusion range in hydrogen (deuterium, tritium) and the scattering cross section. In the diffusion approximation (many scatterings with small energy losses in each) this relation has the form

$$\bar{L} = \bar{R}\sqrt{3\bar{n}\,y}\,, \quad y = 1 - \overline{\cos\Theta}\,,$$

where $\bar{L}$, $\bar{R}$ are the mean "straight-line" and "broken" pathlengths of hydrogen isotopes mu-atoms, $\bar{n}$ is the average number of collisions of mu-atoms with target atoms (molecules) during their lifetime, $\overline{\cos\Theta}$ is the mean cosine of the mu-atom scattering angle in the laboratory frame of reference.

For the first time the cross sections for processes

$$(p\mu)_{1s} + p \rightarrow (p\mu)_{1s} + p \tag{1}$$

$$(d\mu)_{1s} + d \rightarrow (d\mu)_{1s} + p \tag{2}$$

$$(d\mu)_{1s} + p \rightarrow (d\mu)_{1s} + p \tag{3}$$

were measured at Dubna with a diffusion chamber [3], [4] and by the Bologna-CERN group with an electronic technique [5]. With the diffusion chamber [3], [4] the cross sections for processes (1)-(3) were determined by comparison of experimentally found distributions in pathlengths of muonic atoms at different mixture densities, concentrations of deuterium and Z-impurities (carbon, oxygen) with the Monte-Carlo calculated ones. The χ^2-analysis was used for the comparison.

The Monte Carlo analysis of distributions in pathlengths involving the data obtained on lifetimes of mu-atoms and the known theoretical expressions for scattering cross sections for mu-atoms [6], [7] in different spin states yielded the following cross section values (Tables 1, 2)

$$\sigma(p\mu + p) = (167 \pm 30)\cdot 10^{-21}\ \mathrm{cm}^2; \quad \sigma(d\mu + d) = (4.15 \pm 0.29)\cdot 10^{-19}\ \mathrm{cm}^2.$$

In the experiment [5] isotopically pure hydrogen (P = 5.4 atm, 26.2 atm; T = 300K) and deuterium at a pressure of 12.1 atm were used. Inside a target filled with hydrogen (deuterium) there were 90 gold plates (10 μm thick) with a gap of 1.5 mm between them. Cross sections for scattering of $p\mu(d\mu)$ atoms in hydrogen (deuterium) were found by analysing yields and time distributions of meso X-ray γ quanta from Auμ atoms (E_γ^{2p-1s} = 5.8 MeV) formed by muon transfer from $p\mu(d\mu)$ atoms (which arrived at the plates) to Au nuclei. The γ quanta were registered by a NaI(Tl) detector. Variable parameters in analysis of time distributions of delayed γ quanta were the scattering cross section and the initial energy of $p\mu(d\mu)$ atoms.

Analysis of the experimental data [5] yielded the following values of the cross sections (Tables 1, 2) for processes (1) and (2)

$$\sigma(p\mu + p) = (7.6 \pm 0.7)\cdot 10^{-21}\ \mathrm{cm}^2$$

$$\sigma(d\mu + d) = (0.55 \pm 0.20)\cdot 10^{-19}\ \mathrm{cm}^2$$

$E^{\circ}_{p\mu} = (0.55 \pm 0.20)$ eV is the initial energy of $p\mu$ atoms.

Since the experimental and theoretical results obtained before 1979 (see Tables 1, 2) were considerably different, it was necessary to carry out more precise investigations of these processes. In the early 1980s experiments on measurement of cross sections for processes (1) and (2) began at Dubna and CERN.

Figure 1 shows the experimental set up from [8]. The target was a cylindrical vessel of stainless steel, 12.5 cm in diameter, about 70 cm long, with walls 2 mm thick. An assembly of aluminium foils 30 μm thick each was installed inside the target. The assembly consisted either of 86 foils with a gap of 2.1 mm between them, or of 112 foils with a gap of 1.3 mm. In the experiment the target was filled with very pure hydrogen or deuterium. There were three exposures with hydrogen at 3 atm, 10 atm and 26 atm, and one exposure with deuterium at 14 atm.

Two (X_1, X_2) NaI(Tl) detectors registered meso X rays of K series from Oμ(E (K_α) = 133 keV)- and Alμ(E (K_α) = 317 keV) atoms resulting both from diffusion of produced $p\mu(d\mu)$ atoms to foils followed by muon transfer to O and Al nuclei and from muon stops in the material of the foils.

The experiment was carried out with a muon beam from the CERN synchrocyclotron. To determine the background correctly, an experiment with pure helium was carried out at a pressure approximately equal to that of hydrogen.

Table 1: Experimental and theoretical values of the cross section for scattering of $p\mu$ atoms in hydrogen

Experiment

Paper	Hydrogen pressure (atm)	$\sigma(p\mu + H_2)$	$\sigma(p\mu + p)$
		$(10^{-21}$ cm$^2)$	
Dubna [3] (diff.chamber)	4.6; 4.8 23.2 (T = 240K)		167 ± 30
Bologna-CERN [5] (electron method)	26.2; 5.4 (T = 300K)		7.6 ± 0.7
Bologna-CERN [8] (electron method)	26.0 (T = 300K)	32.0 ± 5.0	14.9 ± 1.4
Dubna [9] (electron method)	41.0 (T = 300K)	42.0 ± 8.0	$17.3 \pm 3.3^*$

Theory

Paper	$p\mu$-atom-proton collision energy	$\sigma(p\mu + H_2)$	$\sigma(p\mu + p)$
		$(10^{-21}$ cm$^2)$	
Zeldovich,	0.04		1.2
Gershtein [6]	–"–		
Cohen S. [7]	–"–		8.2
Matveenko [10]	–"–		2.5
Ponomarev [11]	–"–		35
Melezhik [12]	–"–		19
Adamczak [13]	–"–		100 $(p\mu + H)$
Adamczak [14]	–"–	416.0 (0.05 eV)	41.2 (0.05 eV)
Cohen J. [15]	–"–		60
			117.4 $(p\mu + H)$ (0.05 eV)

* found from the ratio $\sigma(p\mu + H_2) \,/\, \sigma(p\mu + p) = 2.42$ [16].

Table 2: Experimental and theoretical values of the cross section for scattering of $d\mu$ atoms in deuterium

Experiment

Paper	Deuterium pressure (atm)	$\sigma(d\mu + d)$ (10^{-19} cm^2)	$\sigma(d\mu + D_2)$ (10^{-19} cm^2)
Dubna [4] (diff.chamber)	$P(H_2 + D_2) = 23.0$ $C_{D2} = (0.14 \div 6.7)\%$ T = 242K	4.15 ± 0.29	
Dubna [7] (diff.chamber)	$P(H_2 + D_2) = 7.0$ $C_{D2} = 94\%$; T = 242K	1.5 ± 0.9	
Bologna-CERN [5] (electron method)	12.1 (isotopically pure deuterium) T = 300K	0.55 ± 0.20	
Bologna-CERN [8] (electron method)	14.0; T = 300K	0.8 ± 0.2	
Bologna-CERN		0.68 ± 0.14 *	

Theory

Paper		$\sigma(d\mu + d)$	$\sigma(d\mu + D_2)$
Zeldovich, Gershtein [6]	The $d\mu$ atom proton collision energy is 0.04 eV	3.3	
Cohen S. [7]		3.5	
Matveenko [10]		1.8	
Ponomarev [11]		1.9	
Cohen J. [15]		1.87 0.05 ev	1.38 $(d\mu + D)$
Adamczak [14]		1.83 0.05 ev	3.73

* The value is obtained by averaging the results of [5], [8].

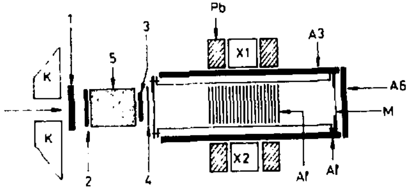

Fig. 1. Lay out of registration equipment in the muon beam:
C — collimator; P — stopping filter; Pb — lead shielding of γ detectors; T — target; Al — aluminium foil; $A_1 \div A_6$ — plastic scintillators; X_1, X_2 — NaI(Tl) detectors.

To determine cross sections for processes (1) and (2), time distributions of γ quanta from $O\mu$ and $Al\mu$ atoms were analysed by the Monte Carlo method on the assumption that a) processes (1) and (2) are described by the constant-value cross section (transitions between levels of hyperfine structure of muonic atoms and dependence of the scattering cross section on the collision energy were ignored), b) scattering is caused by point like particles of mass equal to that of hydrogen (deuterium) molecules, c) angular distribution of scattered muonic atoms is of anisotropic character in the centre of mass system. As an example, Fig. 2 shows time distributions of γ quanta of meso X ray K series of $Al\mu$ and $O\mu$ atoms from experiments with hydrogen at 10 atm and with deuterium at 14 atm. After processing of all data the following values of cross sections for processes (1) and (2) were obtained

$$\sigma(p\mu + p) = (1.49 \pm 0.14) \cdot 10^{-20}\ \mathrm{cm}^2; \quad \sigma(d\mu + d) = (8.0 \pm 2.0) \cdot 10^{-20}\ \mathrm{cm}^2;$$

$$0.1\ \mathrm{eV} \leq E^{\circ}_{p\mu} \leq 0.8\ \mathrm{eV}.$$

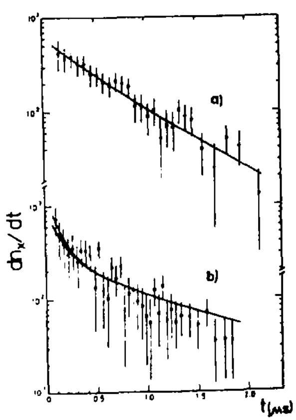

Fig. 2. Time distributions of meso X-ray γ quanta from $Al\mu$ and $O\mu$ atoms (with background subtracted): a — experiment with pure hydrogen at 10 atm, b — experiment with deuterium at 14 atm. Solid lines show fitting results. Two lines in the initial region of spectrum b) show the results of fitting the experimental data on the assumption that the initial energy of $d\mu$ atoms is 0.2 eV and 1 eV, respectively.

In 1983 an experiment [9] on measurement of the cross section for scattering of $p\mu$ atoms in hydrogen was carried out in Dubna. The experimental lay out is shown in Fig. 3. There was a gas target [8] with the volume limited by scintillators of CsI(Tl) detectors 4 and 5. Scintillator 5 was a hollow cylinder 205 mm long, with inner diameter 120 mm and walls 5 mm thick. Scintillator 4 was a disc 120 mm in diameter, 250 μm thick. The scattering cross section were determined from analysis of amplitude and time distributions of meso X ray γ quanta from $Cs\mu$ and $I\mu$ atoms produced by muon transfer from $p\mu$-atoms arrived at scintillator walls of detectors 4 and 5 to Cs and I nuclei. Two NaI(Tl) detectors (dia. 150 × 100 mm^2) registered γ quanta. The experiment involved the following exposures:

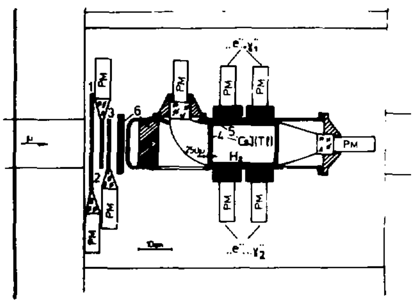

Fig. 3. The experimental lay-out: 1 ÷ 3 monitoring counters: 4, 5 CsI(Tl) scintillators; 6 stopping filter; "e", "γ" electron and γ quantum detectors respectively.

a) the target was filled with isotopically pure hydrogen to the pressure of 41 atm (T = 300K) with the deuterium content below 2 ppm, which eliminated noticeable distortion of the result caused by diffusion of $d\mu$ atoms to scintillators of detectors 4 and 5 ($d\mu$ atoms are formed by muon transfer from $p\mu$ atoms to deuterons);

b) the target was filled with pure helium to the pressure at which the number of muon stops int it was equal to that in pure hydrogen (background experiment);

c) the target was filled with a $H_2 + Xe$ mixture to determine the registrations efficiency for meso X-ray γ quanta from $(Cs, I)\mu$ atoms. Closeness of I, Xe, Cs atomic numbers allows one to consider meso X-ray characteristics of $Cs\mu$-, $I\mu$-, $Xe\mu$ atoms identical;

d) an experiment with a vacuum target;

e) auxiliary experiments aimed at measuring density distribution of stops over the target volume.

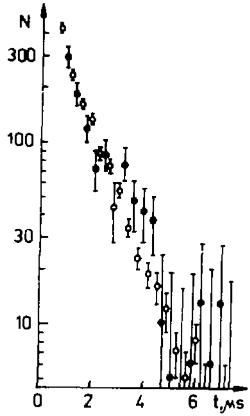

Fig. 4. Time spectra: • — measured distribution of γ quanta from charge exchange of $p\mu$-atoms on the target wall material; o — similar distribution obtained by Monte Carlo simulation at $\sigma(p\mu + H_2) = 42.0 \cdot 10^{-21}$ cm^2.

As an example, Fig. 4 shows the time distribution of meso-X-ray γ quanta from (Cs,I)μ atoms (with background subtracted) resulting from diffusion of $p\mu$-atoms to target walls. To find the relation between the scattering cross section for $p\mu$-atoms and the relative experimental yield α_t of meso-X-ray γ quanta from (Cs,I)μ-atoms and to check sensitivity of the result to various assumed characteristics of scattering, the processes occurring after muons stopped in hydrogen were numerically simulated by the Monte Carlo method. The simulation algorithm involved the following assumptions: 1) *distribution of muon stops over the target volume is isotropic*, 2) *initial* energy of $p\mu$ atoms is 0.18 eV; 3) elastic scattering cross section of $p\mu$-atom by H_2 molecule in the energy range of collision $E \leq 0.18$ eV is constant; 4) on colliding with a hydrogen molecule the mu atom, whose wave length is smaller than the size of the molecule, practically interacts with one of its protons, and yet "feels" that the proton remains bound in the molecule H_2. Since the spacing between rotational energy levels of the H_2 molecule is about 0.01 eV, the rotational energy levels of the molecule can be excited at collision energies from 0.04 eV to 0.18 eV. So, one does not deal with pure elastic collisions of the $p\mu$ atom with the molecule as a whole. That is why the authors of [9] regarded the process $p\mu + H_2 \to p\mu + H_2$ as c.m. isotropic elastic scattering of $p\mu$ atoms by particles with an effective mass $m_p \leq M \leq 2m_p$(m_p is the proton mass); 5) the velocity distribution of molecules with effective mass M is described by the Maxwell formula with the average energy 0.038 eV.

Taking into account the fact that in the given energy range only rotational energy level can be excited in collisions of $p\mu$-atoms with hydrogen molecules (vibrational levels are not excited), the authors of [9] considered a classical dumbbell-like analog of the H_2 molecule with two atoms fixed at a given distance on the axis. Simulation of collisions between $p\mu$ atoms and these molecules taking part in thermal motion with five degrees of freedom showed that the average characteristics of scattering are equivalent to characteristics of collisions between hydrogen mu atoms and particles of mass $M = 1.25$ m$_p$.

The Monte Carlo simulation of the mu atomic and mu-molecular processes in hydrogen with the effective mass of the H_2 molecule yielded the cross section for scattering of $p\mu$-atom by hydrogen molecule:

$$\sigma(p\mu + H_2) = (42.0 \pm 8.0) \cdot 10^{-21}\ \mathrm{cm}^2 .$$

In Fig. 4 one sees the measured time distribution of meso-X ray γ quanta from $(Cs, I)\mu$ atoms and the corresponding simulated distribution at $\sigma = 42.0 \cdot 10^{-21}\ cm^2$. As seen, these distributions do not differ within the statistical errors. Since a usual result of theoretical calculations is a cross section for scattering of $p\mu$-atoms by free protons $\sigma(p\mu + p)$, the authors of [9] used the ratio $\sigma(p\mu + H_2) / \sigma(p\mu + p) = 2.42$ [16] to compare the experimental value of $\sigma(p\mu + H_2)$ with the theoretical one. The derived value of $\sigma(p\mu + p)$ is

$$\sigma(p\mu + p) = (17.4 \pm 3.3) \cdot 10^{-21}\ \mathrm{cm}^2 .$$

As seen from Table 1, the experimental values of the cross section for scattering of $p\mu$ atoms in hydrogen [8], [9] agree within the statistical errors with one another and with the result [12] calculated by numerically solving a multichannel scattering problem in the adiabatic representation of the problem of three bodies interacting by the Coulomb law. As to the data of [8], [9] and the result of [3] obtained with a diffusion chamber, they show considerable difference as before [5]. Noteworthy is also substantial discrepancy between the experimental data [8], [9] and the results of calculation [12] - [15] of cross sections for scattering of $p\mu$ atoms by hydrogen atoms and molecules (Table 1) obtained with allowance for spin effects and impact of H_2 electron shell (all possible rotational and vibrational transitions in hydrogen molecules).

Now the experimental data [19], [20] on measurement of cross sections for scattering of $p\mu$ and $d\mu$ atoms atoms in hydrogen and deuterium are being analysed. The experiment was carried out at PSI (Switzerland) by a method practically analogous to the one used in [5], [8] at hydrogen pressure ranging from 47 mbar to 1520 mbar and deuterium pressure from 94 mbar to 1520 mbar. During the experiment there was an assembly of 50 foils (the gap between them was d = 2.3 mm) or 25 foils (d = 4.6 mm) inside the target. The foils were made of a plastic material $(C_2H_2F_2)$ covered with a layer of Au 100 ± 10 Å. The method for cross section measurement was based on Monte Carlo analysis of time distributions of 356 keV γ quanta arising from de-excitation of ^{196}Pt nuclei resulting from capture of muons by Au nuclei. The aim of the experiment was not only to measure cross sections for scattering of $p\mu$ and $d\mu$ atoms atoms in hydrogen and deuterium but also to get information on the initial energy distribution of muonic atoms of hydrogen isotopes.

Table 2 lists the experimental and calculated values of cross sections for scattering of $d\mu$ atoms in deuterium. Analysing pathlength distributions of $d\mu$ atoms by the Monte Carlo method, the authors of [4], [17] employed the following assumptions. In the epithermal $d\mu$ atom energy range $0.05 \leq E_{d\mu} \leq 45$ eV $d\mu$ atoms are scattered by free deuterons; the angular distribution of scattered $d\mu$ atoms is isotropic in the c.m. system; the energy dependence $\sigma(d\mu + d)$ is taken from [7] (σ (0.05 eV) = 1.5 σ (45 eV)); in the thermal energy range $d\mu$ atoms are scattered by D_2 molecules; D_2 molecules are at rest, and Maxwell motion of D_2 molecules is taken into account only when the average energy of relative motion of $d\mu$ atoms and D_2 molecules is calculated; the "bound" character of a deuteron in the D_2 molecule is taken into account; the angular distribution is isotropic in the c.m. system; the density of scattering centres is equal to the number of deuterons; the scattering centre mass is $2m_d$(m_d is the deuteron mass).

In [5], [8] the Monte Carlo analysis of time distributions of meso X rays from $Au\mu^-$, $Al\mu^-$, $O\mu$-atoms for determination of the $d\mu$ atom scattering cross section in deuterium was carried out with practically the same assumptions as the analysis of the experimental data [5], [8] on measurement of the $p\mu$ atom scattering cross section in hydrogen (the scattering centre mass is $2m_d$).

Table 2 also give the cross section for scattering of $d\mu$ atoms by deuterons averaged over the data of [5], [8]. As seen from Table 2, the experimental results obtained in [4], [7] and in [5], [8] do not agree. There is also considerable difference between them and the calculated results of [6] - [7], [10] - [11], [14] - [15].

Turning to scattering of $d\mu$ atoms by protons, we would like to mention that there has been no correct measurement of the cross section for this process up to now (see Table 3). To know cross sections for process (3) is necessary not only for correct description of kinetics of mu atomic and mu molecular processes in the $H_2 + D_2$ mixture but also for checking the algorithm of calculation of this quantity because theoretical papers indicate that the elastic $d\mu + p$ scattering cross section can be practically zero at the $d\mu$ atom energy $E_{d\mu} \simeq 0.45$ eV in the lab system (Ramsauer Townsend effect). Analysing the present day situation with experimental and theoretical results of determination of the cross section for scattering of $p\mu$ and $d\mu$ atoms in hydrogen and deuterium, one can draw the following conclusions.

1) For correct comparison of the results obtained in [3], [4], [5], [8], [9] one must carry out the Monte Carlo analysis of all experimental data (pathlength distributions of $p\mu$ and $d\mu$ atoms [3], [4], time distributions and yields of meso X ray γ quanta from $Au\mu$ atoms [5], $O\mu$, $Al\mu$ atoms [8], $Cs\mu$, $I\mu$ atoms [9]) using calculated angular distributions of scattered $p\mu$ and $d\mu$ atoms [23]. Thus, the simulation algorithm for scattering of muonic atoms in hydrogen and deuterium must comprise the same assumptions.

2) It is necessary to compare the results obtained in the above way with the results of experiments carried out at PSI [19], [20].

Table 3: Experimental and theoretical values of the cross section for scattering of $d\mu$-atoms in hydrogen

Experiment		Theory		
Paper	$\sigma(d\mu + p)$ $(10^{-21}\ cm^2)$	Paper	$\sigma(d\mu + p)$ $(10^{-21}\ cm^2)$	$\sigma(d\mu + H_2)$ $(10^{-21}\ cm^2)$
Dubna [4] (diff.chamber - $P(H_2 + D_2)$ = 23 atm, C_{D2} = (0.44÷6.7)% T = 242K)	≤ 5	Cohen S. [7]	$0(E_{d\mu} = 0.45$ eV) 5.3 (0.04 eV)	
		Cohen J. [15]	13.0	53.2 $(d\mu + H)$
			(0.05 eV)	
			1.4	3.0
			(1.0 eV)	
		Adamczak [22]	16.6	35.5
			(0.05 eV)	
			3.2	18.7
			(1.0 eV)	
Shiff [21]	$(0.8^{+0.8}_{-0.4})^*$	Melezhik [12]	16.0 (0.04 eV) 0.7 (1.0 eV) 1.8 (3 eV)	

* The result is obtained in [4] by analysis of the $d\mu$-atom pathlength distribution measured in an experiment with liquid hydrogen [21].

3) If there is discrepancy, additional experimental investigation of $p\mu$- and $d\mu$-atom scattering must be carried out, which will help not only to clarify the nature of the discrepancy but also to check correctness of calculation of cross sections for processes (1) and (2). It should be mentioned that the chosen methods and conditions for the experiments must be such that the possibility of any possible systematic errors is reduced to a minimum.

4) To get correct information on the cross section for scattering of $d\mu$-atoms in hydrogen it is necessary to carry out experiments on measurement of this quantity under different experimental conditions.

Finally, we point out an interesting proposal [24] for production of fluxes of practically monoenergetic muonic atoms of hydrogen isotopes and their use for measuring cross sections for scattering of muonic atoms in hydrogen, deuterium and tritium.

Experiments of this type allow direct observation of the Ramsauer Townsend *effect in scattering of $d\mu$ and $t\mu$ atoms in hydrogen. (Besides, neutral fluxes of* $d\mu$ and $t\mu$ atoms will allow more detailed investigation of mu catalysis kinetics in deuterium, tritium, in $H_2 + D_2$, $D_2 + T_2$, $H_2 + T_2$ mixtures.)

All *the above mentioned package of investigations will undoubtedly provide an-*swers to many of the questions arising in the study of $p\mu$, $d\mu$, $t\mu$ atom scattering in hydrogen, deuterium and tritium.

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Быстрицкий В.М. E1-93-450

К вопросу об измерении сечений рассеяния $p\mu-$ и $d\mu-$атомов в водороде и дейтерии

Работа посвящена краткому обзору всей совокупности экспериментов по измерению сечения рассеяния $p\mu-$атомов в водороде и $d\mu-$атомов в водороде и дейтерии. Проведен анализ и сравнение полученных экспериментальных результатов как между собой, так и с результатами вычислений. С целью выяснения природы существующих расхождений между результатами некоторых экспериментальных работ, а также для получения более прецизионной информации о сечениях указанных процессов предложена программа дальнейшего изучения процессов рассеяния мюонных атомов изотопов водорода.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна, 1993

Bystritsky V.M. E1-93-450

On Measurement of Cross Sections for Scattering of $p\mu-$ and $d\mu-$Atoms in Hydrogen and Deuterium

The paper is a brief review of all experiments on measurement of cross sections for scattering of $p\mu-$atoms in hydrogen and $d\mu-$atoms in hydrogen and deuterium. The experimental results are analysed and compared both with one another and with calculated results. A program for further investigation of scattering of muonic atoms of hydrogen isotopes is proposed in order to clarify the nature of discrepancies between some experimental results and to get more precise information about the above processes.

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

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