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NEW MEASUREMENT OF THE ELASTIC SCATTERING CROSS-SECTION OF μ d MUONIC
ATOMS AGAINST DEUTERONS

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ABSTRACT

We have measured the elastic scattering cross-section for the process $\mu d + d \rightarrow \mu d + d$ in ultrapure gaseous deuterium at 14 atm and at room temperature. The result is $\sigma_{dd} = (8 \pm 2) \times 10^{-20} \text{ cm}^2$.

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For the purpose of interpreting or planning experiments in different fundamental branches of muon physics [such as, for example, the elementary muon-proton weak interaction at low energy [1] or the QED effects on the energy levels of muonic hydrogen (μp) or deuterium (μd) atoms [2]] it is necessary to get a picture that is as complete as possible of the diffusion processes

which the μp and μd atoms undergo against protons and deuterons. Given the uncertain situation of the experimental results [2] on the cross-sections for these processes, we have undertaken new measurements, some results of which have already appeared, concerning process (1) [3]. Once the μp atoms have attained their 1S ground state (which mostly occurs within a very short time following their formation) the cross-section for this process is generally expected to depend strongly [2] on the total spin state of the μp systems themselves. This fact provides, in principle, a good tool for investigating the relative population of the triplet and singlet hyperfine structure states of these systems in a given experimental condition, and its evolution in time [4-6]; on the other hand, the comparison of experiment with theory, in this case, is not trivial, since the available predictions nowadays look very different according to the particular approximation followed [7-10].

As regards process (2), the experimental results yield more direct information. Regardless of the theoretical approach, in fact, the cross-section values expected for reaction (2) are similar for μd atoms which are either in the quartet state or in the lower-energy doublet state of the hyperfine structure [7-10]. Therefore, in spite of the fact that the incoherent processes included in reaction (2) may affect the initial population of the quartet and doublet states (at a rate which depends on the experimental conditions), the *effective* value of the cross-section is almost independent of the temperature and density of the deuterium target where the μd atoms are formed. Measurements on this process, then, may more easily provide experimental support to one or the other of the existing theoretical predictions [7-10].

We report here the results of a new measurement of the cross-section for process (2), which was performed using a counter technique with the aim of observing the reaction in the absence of possible sources of systematic errors which might have affected the results of the previous experiments (as will be discussed later).

The experiment was performed at the muon channel of the 600 MeV CERN Synchrocyclotron (SC2), stopping negative muons in ultrapure deuterium^{*)} at 14 atm pressure and at room temperature, and looking at the distribution of the delays required, by the μd atoms formed, to reach^{**)} one of a series of 30 μm thick, regularly spaced (2.1 mm) aluminium foils immersed in the deuterium itself. The apparatus used was the same as that previously exploited to study process (1) at 26 atm hydrogen pressure [3]. The effective muon beam was $18,000 \text{ particles s}^{-1}$. The rate of muons stopping in the whole target was 4800 s^{-1} . Since in such a target the fraction of μp or μd atoms formed that attain the aluminium foils decreases for increasing values of the relevant scattering cross-section, and the cross-section predicted for process (2) is larger [7-10] than the one we measured for process (1) at 26 atm [3], we chose 14 atm as a convenient working condition for observing process (2). Furthermore, this choice allowed us to check the performances of the apparatus in measuring higher cross-sections at lower pressure conditions.

The details of the experimental arrangement have been given elsewhere [3]. Here it should be remembered that the time (t_{stop}) at which one negative muon was stopping in the target was given by a fast coincidence-anticoincidence signal between a conventional beam telescope and a box of plastic scintillators (A_1 detectors) enclosing the target itself; and that the time (t_X) required by one μd atom

*) The deuterium gas was filtered through a palladium purifier before entering the target. The residual impurity level, measured after each run, was always below the sensitivity of a 5830A HP gas chromatograph (2 ppm).

***) The μd atoms are neutral systems, of very small atomic dimensions ($a_{\mu} = 2.56 \times 10^{-11} \text{ cm}$). Therefore, they diffuse throughout the surrounding deuterium medium, undergoing process (2), and may eventually attain one of the aluminium foils.

to attain an aluminium foil was determined by observing [by suitable NaI(Tl) detectors] the K-series^{*} muonic X-rays (X signal) promptly released following the transfer reaction [11]

of the muon from the μd system to an atom Y of aluminium ($Y = Al$) or oxygen ($Y = O$), belonging to the natural layer of Al_2O_3 (600 to 1000 Å thick) present on the aluminium foils. Bearing in mind the characteristic energies of the Lyman series of μO [$E(K_\alpha) = 133$ keV] and of μAl [$E(K_\alpha) = 347$ keV], and the energy resolution of the NaI(Tl) detectors used (13% FWHM at 347 keV), the data were recorded over an energy interval ranging from 50 to 600 keV.

The A_i plastic scintillators surrounding the target were also used to detect the muon decay electrons (when they came at a time t_e larger than t_X) in delayed coincidence with the X signal [(X,e) coincidence]. The data recording was triggered by the (X,e) signal: for each event, together with other information, the amplitude of the signal from the X-ray counters and the delays ($t_X - t_{stop}$) and ($t_e - t_X$) were stored on magnetic tape.

The analysis of the data was carried out separately for the two energy intervals $\Delta E_O = (70-200)$ keV and $\Delta E_{Al} = (300-550)$ keV, which were chosen to include the whole amplitude range accessible to the K-series X-rays from μO and μAl atoms, respectively. The background counts in both energy intervals were due to random coincidences between nuclear capture products (coming from muons directly stopped within the target solid materials, Fe and Al) and accidental counts within the A_i detectors. This background was eliminated by subtracting out auxiliary runs, where the target was filled with helium at 14 atm pressure (*helium runs*)^{**}.

*) The K-series X-rays are due to the $nP \rightarrow 1S$ Lyman transitions. The notation followed is K_α for $2P \rightarrow 1S$, K_β for $3P \rightarrow 1S$, ..., $K_{tot} = K_\alpha + K_\beta + \dots$; all the transitions leading to an $n = 2$ state give rise to the Balmer series (L-transitions).

**) The $(\mu He)^+$ ion formed in this way cannot transfer the muon to the aluminium foils.

In the ΔE_{Al} interval, the energy resolution of the NaI(Tl) detectors allowed us to study to some extent the structure of the K-series X-rays of μAl atoms formed through process (3). As reported elsewhere [12], it turned out that the ratio (K_{α}/K_{tot}) is, in this case, larger than for μAl atoms formed through the muon transfer reaction $\mu p + Al \rightarrow \mu Al + p$ [13]; this might result in a higher proportion of μAl L-lines [$E(L_{\alpha}) = 64$ keV] released in cascade with the K-series spectrum, and observed in the present measurements in the relevant energy interval. Given the energy cuts defining the ΔE_0 interval, and the energy resolution of the detectors used, a fraction of the μAl L-line spectrum might contaminate the events collected in the ΔE_0 interval. For this reason, we took particular care in examining the time distribution $(dn_e/dt)_0$ of the muon decay electrons detected in sequence to the X-rays events within the ΔE_0 range (see fig. 1). As seen from the figure, this spectrum reproduces the lifetime of μO atoms [14], proving that the associated X-rays are indeed due to muon transfer to oxygen nuclei. No appreciable component having the characteristic lifetime of μAl atoms [15] is present in this distribution: the contamination of L-line X-rays from μAl within the ΔE_0 events, if present, is therefore negligible within the quoted experimental errors.

After subtraction of the background, the $(dn_X/dt)_0$ time distribution ($t = t_X - t_{stop}$ in this case) of the delayed X-rays detected within the ΔE_0 energy interval, normalized to the over-all efficiency of the apparatus to detect X-ray signals in the ΔE_{Al} range, was summed to the corresponding $(dn_X/dt)_{Al}$ distribution of the events collected within the ΔE_{Al} range itself. The cumulative distribution obtained in this way is shown in fig. 2. The errors include the inaccuracies due to the subtraction of the *helium runs*, as well as the one with which the mentioned efficiency normalization factor was known [16]. This distribution was analysed by a Monte Carlo method, which followed the diffusion of one μd atom through process (2), starting from its formation time ($t = t_{stop}$) in the gaseous deuterium until it disappeared through some inelastic channel, such as muon decay or nuclear capture, μd ion formation, or eventually process (3) (at time $t = t_X$). The theoretical distributions of the delays $(t_X - t_{stop})$ were then fitted to the experimental

(dn_X/dt) spectrum by a χ^2 analysis, leaving the cross-section σ_{dd} for process (2) and the initial energy $E_{\mu d}$ of the μd atoms as free parameters. A unique effective value was assumed in the calculation for σ_{dd} , for the reasons already specified. The effective number of muons stopped in the deuterium gas, to be referred to the distribution (dn_X/dt), was determined starting from the number of *prompt* K-series X-rays from μAl (due to direct muon stopping in the Al foils), observed in correspondence with the delayed spectrum of fig. 2, after suitable scaling for the stopping power ratio of the aluminium foils to the useful volume of deuterium. Other parameters (such as the effective rates of different μ -molecular processes [2], the deuterium density and temperature, and the distance between the foils) were fixed by the conditions of measurement.

As a result of the analysis, we get, for process (2) occurring at 14 atm of deuterium pressure and at room temperature,

$$\sigma_{dd} = (8 \pm 2) \times 10^{-20} \text{ cm}^2. \quad (4)$$

In order to have a further understanding of the meaning of the present result, the following points should be retained:

i) Estimate of the error. The value (4) represents a cross-section about five times larger than the one measured by the same apparatus for process (1) at 26 atm hydrogen pressure [3]. At such higher cross-section, opposite to the case of the previous measurement, the central value of eq. (4) is not entirely independent of the initial energy $E_{\mu d}$ of the μd muonic atom. Therefore the error given, besides including the inaccuracies due to the fitting procedure and those pertaining to the different parameters involved in the Monte Carlo calculation, also includes an additional excursion due to the lack of knowledge on $E_{\mu d}$ [which was left to vary between the thermal value (0.038 eV) and 2 eV] [3-5]. Conversely, if for $E_{\mu d}$ one could assume a value provided by some independent information, the error in eq. (4) would be somewhat smaller.

ii) Lower limit of the μd atom initial kinetic energy. In the present experimental conditions (which were chosen to optimize the number of events, bearing in mind the expected cross-sections range) the method used is fairly insensitive to

$E_{\mu d}$. Within the range of values allowed by eq. (4), however, the lowest values of $E_{\mu d}$, i.e. those close to the thermal limit, are less compatible with the results shown in fig. 2 than those belonging to the remaining energy interval. This suggests that the μd atoms, too, begin to diffuse with an initial energy which is larger than the thermal value, as was proved to be the case for μp atoms undergoing process (1) [3-5].

iii) Comparison with previous experiments. As seen from table 1 [5,17], the result (4) is compatible within experimental errors with the previous value given by the Bologna-CERN group [5], which was obtained by a similar method. However, besides other technical differences, it should be recalled that in the preceding experiment gold foils were used (instead of aluminium ones); and that the measurement was based on the observation of only the central part of the K_{α} peak of the μAu atoms formed through process (3). The agreement between these two experimental results is therefore conditioned by the hypothesis that the muon transfer effect on the Lyman series of high-atomic-number muonic atoms (such as μAu) is much smaller than in the case of low-atomic-number elements (such as μAl) [12,13]. On the other hand, the experimental result from the Dubna group [17] was obtained by a diffusion chamber technique, for μd atoms formed (through the isotope exchange reaction $\mu p + d \rightarrow \mu d + p$) with an initial energy of 45 eV. Here it should be remarked that process (2) was observed in competition with the scattering reactions $\mu d + p \rightarrow \mu d + p$ and $\mu d + Y \rightarrow \mu d + Y$ (where Y stands for an atom of alcoholic impurities which were present within the deuterated hydrogen of the chamber in known concentrations). Since there is as yet no well-established experimental result for these two last processes [2], the cross-section value [17] given in table 1 might have to be corrected if independent information were provided on the two mentioned competing channels.

As a concluding remark, we should like to mention that the present result is closer to the recent theoretical estimates (see table 1) by Ponomarev et al. [9,10] (and then supports their calculation approach) than to those obtained in previous theoretical work [7,8].

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Table 1

Summary of experimental (E) and latest theoretical (Th) results on the elastic scattering cross-section for the process $\mu d + d \rightarrow \mu d + d$

Authors	Cross-sections (units of 10^{-20} cm^2)		
	σ_{dd}	$(\sigma_{dd})_{3/2}^{\text{a)}}$	$(\sigma_{dd})_{1/2}^{\text{a)}}$
Dubna ^{b)} (E)	41.5 ± 2.9		
Bologna-CERN ^{c)} (E)	5.5 ± 2.0		
Bologna (present work) (E)	8 ± 2		
Ponomarev et al. ^{d)} (Th)		14	19

a) Values referring to μd atoms in the quartet ($J = 3/2$) and doublet ($J = 1/2$) total spin state, respectively.

b) See reference 17.

c) See reference 5.

d) See reference 10.

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Figure captions

- Fig. 1 : Background-subtracted time distribution (dn_e/dt) (where $t = t_e - t_X$) of the electrons detected (at time t_e) in sequence to delayed X-rays, coming at time t_X within the ΔE_0 energy range. Minimum delay ($t_e - t_X$): 200 ns. Minimum delay ($t_X - t_{stop}$) of associated X-rays: 100 ns. The full curve represents the best fit to a single negative exponential distribution, yielding a lifetime $\tau_{exp} = (1805 \pm 250)$ ns ($\chi^2 = 9$; number of points 14); this value should be compared to the mean lifetime of the $\mu 0$ atoms, $\tau_0 = (1816 \pm 11)$ ns (see reference 14).
- Fig. 2 : Background-subtracted time distribution (dn_X/dt) (where $t = t_X - t_{stop}$) of the delayed X-rays collected within both the ΔE_0 and ΔE_{A1} energy intervals. The events are normalized to the over-all efficiency of the apparatus to detect muonic X-rays within the ΔE_{A1} energy range. Minimum delay of the associated decay electrons: ($t_e - t_X$) = 200 ns. The continuous line represents the theoretical distribution obtained from the Monte Carlo calculation for $\sigma_{dd} = 8 \times 10^{-20}$ cm². The spread of the curve at the earlier delays considered shows how the theoretical distribution changes if the initial energy of the μd atoms is left to vary between 0.2 and 1 eV (see references 3 to 5). Typical χ^2 value: 37; number of points: 36.

FIG. 1

FIG.2