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NEW MEASUREMENT OF THE CROSS SECTION FOR THE ELASTIC SCATTERING

PROCESS $\mu p + p \rightarrow \mu p + p$ IN GASEOUS HYDROGEN AT 26 ATMOSPHERES

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ABSTRACT

We have measured the elastic scattering cross section for the process $\mu p + p \rightarrow \mu p + p$ in ultra-pure gaseous hydrogen at 26 atm and at room temperature. The result is $\sigma = (1.4 \pm 0.2) \times 10^{-20} \text{ cm}^2$.

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Experimental investigations on the diffusion processes [1] which the muonic hydrogen (μp) atoms undergo against protons are currently considered as a basic tool to get information on the population of the hyperfine structure levels of the μp system, a problem which is deeply connected with the field of the elementary muon-proton weak interaction at low energies [2]. The results of experiment available so far on the cross section for the scattering process

are affected, however, by a very significant discrepancy (table 1) [3,4]. The relevant theoretical predictions, which seemed in the past well founded [1] are also under discussion [5,6]. Therefore, the situation demands further effort in order to be clarified.

A first meaningful step in this direction would certainly be achieved if one were able to eliminate the mentioned experimental discrepancy, deciding in favour of either one of the previous results. We report here on a new measurement of the cross section for process (1), which was performed with this purpose, using a target of ultra-pure gaseous hydrogen at 26 atm and at room temperature. The experiment was based [4] on observing the differential time distribution (dn_X/dt) of the delays with which the μp atoms - formed in hydrogen at a time t_{stop} - attain one of a series of thin metallic foils, dipped in the hydrogen gas itself. Since this occurs (at time t_X) after the μp atoms have diffused against the surrounding hydrogen atoms [7], the (dn_X/dt) distribution (where $t = t_X - t_{\text{stop}}$) contains information on the cross section for process (1).

In the present case, the hydrogen container was a stainless steel tank (entrance window 1 mm, side surface 2 mm thick, internal diameter 12.5 cm), where 86 aluminium foils were also set, each 30 μm thick, and spaced 2.1 mm apart from one another (fig. 1). The tank was vacuum tight down to 3×10^{-7} mm Hg. Careful outgassing was carried out before filling it with hydrogen, which was made ultra-pure by means of a palladium filter [8].

The experiment [9] was carried out at the muon channel of the CERN 600 MeV Synchro-Cyclotron (SC2), stopping in the target low-momentum negative muons. The effective muon beam was of 17 000 particles s^{-1} . The rate of muons stopping in the whole target was 4500 s^{-1} .

When a μp muonic atom, initially formed in the hydrogen gas, attained one aluminium foil (which was covered by a thin natural layer of Al_2O_3), it went through the fast transfer reaction

where Y stands in turn for Al or O. The excited $(\mu Y)^*$ muonic atom formed in the final state of such a process decays promptly into the 1S ground state, releasing a series of characteristic X-ray lines. In the present experiment, the time t_X was measured by recording the K-line [10] X-rays emitted from the de-exciting μAl or μO systems, by means of properly chosen NaI(Tl) detectors (X_1 and X_2 in fig. 1). The stopping time t_{stop} of the incoming muons was given by the STOP signal from the plastic scintillators arrangement ($STOP = 1, 2, 3, 4 - (\sum A_i)$), where $(-)$ means "not". The X_i detectors were set in delayed coincidence with the STOP pulse ($X = (STOP, (X_1 + X_2))$) to signal the time t_X (the time resolution was 25 ns FWHM). The A_i plastic scintillators were used in turn to detect the muon decay electrons from the μO or μAl atoms, coming at time t_e , in delayed coincidence with the X pulse.

The data recording was triggered by the X coincidence. For each event, together with other information of relevance, the amplitude of the X_i signal and the delays $(t_X - t_{stop})$ and $(t_e - t_X)$ (the latter when the electron was present) were stored on magnetic tape via a 2100 HP computer. The data were taken over an energy interval ranging from 50 to 600 keV, in order to accept both the K-lines from μO ($E(K_\alpha) = 133$ keV) and from μAl ($E(K_\alpha) = 347$ keV). The energy resolution of the X_i counters (each 7.6 cm in diameter and 7.6 cm thick) was of 13% FWHM at 347 keV.

The prompt 347 keV X-rays, due to the muons directly stopped within the aluminium foils, allowed a continuous on-line check of the calibration figure, and the optimalization of the rate of muons stopping in the gas. The range curve obtained in this way had a width of 4 cm of polyethylene at half maximum.

The analysis was performed operating first an off-line amplitude selection on the signals from the X_1 counters, which restricted the range mentioned above to the energy intervals $\Delta E_0 = (70-200)$ keV and $\Delta E_{Al} = (300 - 550)$ keV. This choice allowed the inclusion also of K-line transitions of order higher than K_α , which preliminary measurements had proved [11] to represent a quite significant contribution to the K-spectrum of μAl after the muon transfer reaction [2].

The background counts within the events selected further through the (STOP + delayed X + delayed electron) sequence were mostly random coincidences between nuclear capture products (due to those muons directly stopping in the target walls or in the aluminium foils) and accidental counts within the A_1 plastic scintillators. This background was subtracted out by auxiliary runs (helium runs) alternated with the hydrogen ones, which were performed filling the target with pure helium at 26 atm: the $(\mu He)^+$ ion formed in this way, in fact, cannot transfer the muon to another element.

After this subtraction, the time distributions (dn_e/dt) of the electrons detected in sequence to the delayed X-ray signals collected within the ΔE_0 and ΔE_{Al} intervals showed the characteristic lifetimes of negative muons within the $\mu 0$ and μAl atoms respectively (fig. 2) [12,13] confirming that these events were indeed due to the muon transfer reactions (2) [14]. A few runs (which were performed under unstable machine conditions), where the (dn_e/dt) distributions showed a residual flat component after background subtraction, were discarded.

The background-subtracted time distribution (dn_x/dt) , including the delayed X-rays observed within both the ΔE_0 and ΔE_{Al} intervals (normalized to the over-all efficiency of the apparatus for the events belonging to the ΔE_{Al} interval) is shown in fig. 3. The errors include the inaccuracies due to the subtraction of the helium runs.

The value of the cross section effective for process (1) was obtained by fitting the experimental results of fig. 3 to the predictions of a Monte-Carlo calculation, where the μp atom was followed from the time of its formation until its disappearance through the inelastic channels (such as muon decay, muon nuclear capture, or formation of $\mu p p$ molecular ions) or through the transfer reactions (2). The effective cross section σ was left as a free parameter, together with the initial energy $E_{\mu p}$ of the μp system. Other variables, such as the hydrogen density and temperature, and the distances between the aluminium foils, were fixed by the conditions of measurement. The effective number of muons stopped in hydrogen, to be related to the (dn_X/dt) distribution of fig. 3, was obtained from the spectrum of the prompt K-lines from μAl observed during the runs, after suitable scaling for the stopping power of hydrogen at 26 atm with respect to that of aluminium [15].

The best fitting distribution (see the continuous curve in fig. 3) corresponds to the values

$$\sigma = (1.4 \pm 0.2) \times 10^{-20} \text{ cm}^2 \quad (3)$$

and

$$E_{\mu p} = (0.11 \pm 0.03) \text{ eV}, \quad (4)$$

with a χ^2 of 36 over 36 experimental points. The errors include the one due to the fitting procedure, as well as the systematic inaccuracies with which the different parameters involved in the Monte-Carlo calculation were known.

Referring to these results, the following considerations hold:

- (i) The central value (3) turns out to be independent of the choice of the initial energy $E_{\mu p}$ within a range going from the thermal value $(3/2) KT = 0.04 \text{ eV}$ up to about 1 eV.
- (ii) Eq. (4) gives a value of the initial energy $E_{\mu p}$ which is bound to the simplified analysis performed (where possible transitions were disregarded between the hyperfine structure states of the μp system [1]). This result indicates however, that the μp systems begin

to diffuse against the surrounding hydrogen atoms with an effective initial energy which is fairly close to (although somewhat larger than) the thermal limit. At such small energies, it can be shown [3,4] that the systematic error due to the fact that the μp atoms collide against protons which are bound in hydrogen molecules is smaller than the experimental error given in eq. (3).

- (iii) Referring to the main purpose of the present measurement, one can conclude that - although there is not a complete agreement with the previous Bologna-CERN experiment [16] the present result excludes the value obtained by the Dubna group [3].
- (iv) Unlike in the past [1] the recent developments of theory are yielding fairly unstable predictions [5,6]. This makes it more difficult to compare the result [3] with theoretical expectations, with the aim of getting information: (a) on the contributions of the different scattering processes - which may involve transitions between the hyperfine structure states of the μp system - to the effective cross section (3); and (b) on the true value of the initial energy $E_{\mu p}$. For these purposes, however, further measurements on the cross section for process [1], performed at lower hydrogen pressures, will doubtlessly be helpful in clarifying the situation.

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- [7] We recall here that the μp systems are electrically neutral and have unusually small atomic dimensions ($a_{\mu} = 2.56 \times 10^{-11}$ cm).
- [8] The impurity level of the hydrogen gas used was checked after each run to be below the sensitivity of a 5830A HP gas chromatograph (2 ppm).
- [9] CERN code of experiment: SC 63.
- [10] The K lines refer to the $nP \rightarrow 1S$ transitions: K_{α} to $2P \rightarrow 1S$, K_{β} to $3P \rightarrow 1S$, and so on.
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- [15] The rate of muons stopping in oxygen was less than 10^{-2} of those stopping in aluminium, given the reduced thickness of the Al_2O_3 layer (less than 1000 Å).
- [16] In the experimental apparatus of ref. [4] gold interfaces ($Z_{\text{Au}} = 79$) were used, instead of aluminium ones. The experiment was based on the observation only of the K_{α} line from (μ Au).

TABLE 1

Summary of the experimental results on the elastic
scattering cross section σ of μp atoms against protons

Authors	Technique	Hydrogen pressure (abs. atm)	$\sigma^{(a)}$ (units of 10^{-21} cm^2)
Dubna ^(b)	Diffusion chamber	up to 23 ^(c)	173 ± 19
Bologna-CERN ^(d)	Counters	26.2 ^(e)	6.5 ± 1.0
Bologna (present work)	Counters	26 ^(e)	14 ± 2

- (a) Effective value of the cross section, obtained by analyzing the data disregarding possible transitions between the hyperfine structure states of the μp system.
- (b) See ref. [3].
- (c) The hydrogen in the diffusion chamber contained known admixtures of alcoholic impurities. The result is obtained from three different measurements, at the pressures of 4.6, 4.8 and 23.2 atm.
- (d) See ref. [4].
- (e) The gaseous hydrogen was ultra-pure.

FIGURE CAPTIONS

Fig. 1 Simplified scheme of the experimental layout: C = last collimator (the arrow indicates beam direction); P = Polyethylene moderator; Pb = 5 cm thick lead screen; T = stainless steel tank; Al = aluminium foils; 1 - 4 = beam telescope; $A_1 - A_6$ = fast anticoincidence, and delayed coincidence plastic scintillators (A_2 and $A_4 + A_5$, which close the scintillator box on both sides parallel to the plane of the figure, are not shown); X1, X2 = NaI (Tl) detectors.

Fig. 2 Background-subtracted time distributions ((dn_e/dt) , where $t = t_e - t_X$) of the electrons detected in sequence to the delayed X signals (minimum delay $t_X - t_{\text{stop}} = 100$ ns). The straight lines correspond to the best fits to negative exponential distributions of lifetime τ_{exp} :

(a) Energy interval of associated X-rays: $\Delta E_0 = (70-200)$ keV. $\tau_{\text{exp}} = (1730 \pm 117)$ ns; $\chi^2 = 19$; number of points: 21. Number of events for $100 \text{ ns} \leq t_e - t_X \leq 6000 \text{ ns}$ (normalized to the efficiency of the apparatus for the X-rays belonging to the ΔE_{Al} interval): 5367 ± 450 . The lifetime of negative muons in the $\mu 0$ atom is (1816 ± 11) ns (ref. [12]).

(b) Energy interval of associated X-rays: $\Delta E_{\text{Al}} = (300-550)$ keV. $\tau_{\text{exp}} = (895 \pm 74)$ ns; $\chi^2 = 9$; number of points: 16. Number of events for $100 \text{ ns} \leq t_e - t_X \leq 6000 \text{ ns}$: 4254 ± 345 . The lifetime of negative muons in the μAl atom is (880 ± 10) ns (ref. [13]).

Fig. 3 Background subtracted differential time distribution (dn_X/dt) of the delayed X-ray signals detected in the present measurements after negative muons had been stopped in the hydrogen gas. The events presented are those corresponding to the (dn_e/dt) distributions shown in fig. 2. Full curve: best-fitting theoretical distribution obtained from the Monte-Carlo calculation.

fig.2

fig.3