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TRIPLET STATE LIFETIME FOR $(\mu p)_{1S}$ MUONIC ATOMS IN GASEOUS HYDROGEN

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ABSTRACT

The lifetime τ_T of the triplet state for $(\mu p)_{1S}$ muonic atoms is evaluated as a function of the hydrogen pressure, starting from recent experimental results obtained at CERN on the scattering cross-section for the process $(\mu p + p \rightarrow \mu p + p)$. It is found that τ_T is significantly smaller than expected on the basis of previous calculations.

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1. INTRODUCTION

Starting from the initial statistical mixture ($\frac{3}{4}$ of triplet and $\frac{1}{4}$ of singlet), the relative population of the hyperfine structure states of the $(\mu p)_{1S}$ muonic atoms formed in gaseous hydrogen changes with time, at a rate which is governed by the incoherent scattering process [1]

$$(\mu p)_T + p \rightarrow (\mu p)_S + p \quad (1)$$

(the indices T and S denoting triplet and singlet states, respectively). At room temperature [$(\frac{3}{2})KT = 0.038$ eV], once the μp atoms have been slowed down from their initial energy (which may be as high as a few eV), to an energy sufficiently smaller than the hyperfine structure separation

$$\Delta E_{\mu p} = 0.183 \text{ eV} , \quad (2)$$

this process becomes irreversible. As a general trend, therefore, the μp atoms formed at time $t = 0$ will tend to depopulate the triplet state in favour of the lower-energy singlet one; starting from its zero-density value (which practically coincides with the $2.2 \mu s$ muon lifetime) the lifetime τ_T of the triplet state will then be a decreasing function of the hydrogen pressure.

Since the muon nuclear capture rate by protons [2] depends strongly on the total spin state of the muon-proton system, to know the value of τ_T at the relevant pressure conditions is a piece of essential information to obtain a significant comparison of the experimental results on the muon nuclear capture in gaseous hydrogen with the predictions of the V-A weak interaction coupling theory [3]. From this particular point of view, the present interest is to investigate whether conditions of reasonably low hydrogen density exist, where the triplet state keeps alive for a substantial fraction of the muon lifetime.

Using different theoretical models [1,4,5], this can, in principle, be done starting from the experimental results on the cross-section for the general process

$$(\mu p) + p \rightarrow (\mu p) + p \quad (3)$$

to which not only reaction (1) (cross-section σ_{TS}) contributes, but also the reverse reaction (cross-section σ_{ST}) and the two coherent scattering channels (no spin transition, cross-sections σ_{TT} and σ_{SS}).

The early experimental results on process (3), however, which were obtained by different techniques by a Dubna group [6] and by a Bologna-CERN group [7], were affected by a discrepancy of about a factor of 20. With the desire to make some valid predictions on τ_T from this type of data, it was then necessary to clarify the experimental situation. A new measurement for the cross-section of process (3) has recently been performed; the result obtained [8] is nearer to the result of ref. 7. Here one should mention that a first calculation of τ_T at different hydrogen pressures was carried out by Matone [9], starting from the results of the Bologna-CERN experiment itself. However, since the latter are not fully compatible with the recent results [8], we have performed a new calculation, trying to evaluate τ_T within the frame of the new experimental information and of the existing theoretical models. The purpose of this letter is to present the results of this type of analysis.

2. THEORETICAL MODELS

Analytical expressions of the four cross-sections σ_{TS} , σ_{ST} , σ_{TT} , and σ_{SS} were provided by Zel'dovich and Gershtein [4], in terms of the scattering lengths a_u and a_g for the states of different symmetry with respect to the interchange of the two nuclei in the ($\mu p + p$) system. Particular accent was laid on the energy dependence of the scattering parameters in the more refined analysis later carried out by Ponomarev et al. [5]. In the following, we shall refer to these [5] formulae as the GP model. A second important step in the direction of reproducing the actual conditions of experiment was to include in the theoretical description detailed corrections due to the fact that the μp atoms are actually scattering against hydrogen molecules (rather than against free protons), which are endowed with internal degrees of freedom: this was first done by Matone [9] (M model).

For the present analysis, we assumed separately the expressions of the various scattering cross-sections provided by the GP model and by a combined model,

constructed by us, which associated with the GP model the corrections due to the presence of the hydrogen molecules, along the lines followed by Matone (GPM model). The experimental time distribution of the μp diffusion times observed by us at 26 atm [8] were fitted to the predictions of a Monte Carlo method, which followed the μp atom along its successive scattering processes, from the time of its formation until its disappearance through the various possible inelastic channels. The scattering length a_u was set at the currently accepted value $a_u = 3.7$ (in units of $a_\mu = 2.56 \times 10^{-11}$ cm), since its influence on the present scattering problem is generally recognized to be small [4,5]. The scattering length a_g , instead, was left as a free parameter, together with the μp atom initial energy $E_{\mu p}$. As a result of this procedure, we got for a_g the two values $a_g(\text{GP}) = -17 \pm 1$, and $a_g(\text{GPM}) = -13 \pm 0.5$, which correspond to the best fit of the theoretical distributions which the GP and GPM model provided to the experimental results. Both values are independent of the initial kinetic energy $E_{\mu p}$, which was left to vary between 0.038 and 2 eV.

3. TRIPLET STATE LIFETIME

For both models, a second Monte Carlo calculation was then performed, to evaluate under different pressure conditions the fraction F_T of triplet states surviving at a time t following the μp atom formation: in this step, the two values $a_g(\text{GP})$ and $a_g(\text{GPM})$ were retained for the GP and GPM models, respectively. Some typical results are shown in fig. 1, from which it is seen that while a certain difference is verified at early times between the predictions of the GP and GPM models, the long-term behaviour of the corresponding curves is similar. The initial bump in the GPM function is most likely due to molecular effects, as well as [9] the initial flat behaviour of the dashed curve, which was derived from the Matone calculation. The trend of this last curve is significantly different from the other two: this is due to a computation error and not to basically different assumptions.

The final predictions obtained from the present analysis are summarized in Fig. 2, where τ_T is given as a function of the hydrogen pressure. The deviation which gives rise to the dashed region includes at each pressure the results

obtained: a) by running separately the Monte Carlo calculations based on the GP and GPM models; b) by varying in both cases a_g within the limits -12.5 to -18; c) by varying the initial energy $E_{\mu p}$ of the μp atom within the range 0.11 to 2 eV. (The lower limit was suggested by the analysis performed in ref. 8; the upper limit was chosen as a typical number in the currently accepted upper range of possible $E_{\mu p}$ values [1].)

For reference, the points taken from Matone's work are also plotted. When introduced in the present models, the scattering parameter values used by Matone ($a_u = 5$, $a_g = -11.2$) provided results on τ_T which are well contained within the dashed region.

4. CONCLUSIONS

The following conclusions hold:

- i) On the basis of the present calculation, one deduces that the $(\mu p)_{1S}$ triplet states are living for significantly shorter times than was expected from the previous analysis [9]. Within the limits of both the quoted (GP and GPM) models, and the mentioned ranges for the relevant parameters, this conclusion is valid regardless of the values of the leading parameter a_g and of the initial energy $E_{\mu p}$.
- ii) Irrespective of the theoretical model [10], it is generally accepted that the effective cross-section when the μp atoms still are in the initial statistical mixture of triplet and singlet states is larger (by at least a factor of 10) than the cross-section σ_{SS} which holds when the μp atoms have irreversibly attained the lower energy singlet state. From fig. 2, one may conclude that an increase of the effective diffusion cross-section should be experienced only at low-pressure conditions, and at very early times following the muonic atom formation.
- iii) Further theoretical work is in progress, which is expected to improve the accuracy of the existing models [11,12]. For the present, it may be interesting to notice that the preliminary results by Ponomarev et al. [12] are providing transition cross-sections σ_{TS} which are even larger than those

evaluated in the past [4,5], so that one might expect that the forthcoming theoretical results may suggest even shorter τ_T lifetimes than those reported in fig. 2.

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Figure captions

- Fig. 1 : Ratio $F_T = [N_{\mu p, T}(t)]/[N_{\mu p, \text{tot}}(t)]$ of the number $N_{\mu p, T}(t)$ of $(\mu p)_{1S}$ atoms which at time t following their formation are in the triplet state, to the total number $N_{\mu p, \text{tot}}(t)$ of $(\mu p)_{1S}$ atoms still living at time t . The three curves represent the predictions obtained by the present analysis following the GP, GPM, and M models discussed in the text. The figure refers to μp muonic atoms formed in hydrogen at the pressure of 2 atm, with an initial energy of $E_{\mu p} = 0.8$ eV.
- Fig. 2 : Lifetime τ_T of the triplet state in $(\mu p)_{1S}$ muonic atoms as a function of the hydrogen pressure. Dashed region: predictions obtained in the present work. The points outside the dashed area are those obtained by Matone (see ref. 9).

Fig. 1

Fig.2