MEASUREMENT OF THE ORTHO-PARA TRANSITION RATE IN THE $p\mu p$ MOLECULE
AND DEDUCTION OF THE PSEUDOSCALAR COUPLING CONSTANT g_p^μ

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ABSTRACT

The ortho-para transition rate in the $p\mu p$ molecule has been found experimentally to be $\lambda_{OP} = (4.1 \pm 1.4) \times 10^4 \text{ s}^{-1}$. Our recent result for the muon capture rate in liquid hydrogen can now be interpreted to extract the ortho-molecular capture rate: $\lambda_{OM} = (531 \pm 33) \text{ s}^{-1}$. A deduction of the pseudoscalar coupling constant g_p^μ is presented: we find $g_p^\mu = 8.7 \pm 1.9$.

(Submitted to Physics Letters)

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We have recently reported [1] a novel measurement of the rate in liquid hydrogen of the capture process

which was the first obtained by comparing the lifetime τ_{μ^-} of μ^- stopped in liquid hydrogen with the positive muon lifetime τ_{μ^+} , avoiding the difficulties of detecting the outgoing capture neutrons from reaction (1).

In order to interpret this result in terms of the fundamental weak-coupling constants, the quantum state from which the capture proceeds must be known. It is well established now, from experiment and theory, that

- i) the μp atom forms rapidly ($0.5 \mu s$) a $p\mu p$ orthomolecule [2,3];
- ii) the transition rate λ_{OP} to the ground para state is small compared with the free muon decay rate λ_0 [4,5]. The rate λ_{OP} has so far been assumed to be negligible on the basis of a theoretical consideration [4] and of a poor experimental limit [6,7] $(4.2 \pm 4.2) \times 10^4 s^{-1}$.

When λ_{OP} differs from zero the measured capture rate in liquid hydrogen λ_c is a function of λ_{OM} and λ_{PM} , capture rates respectively from the ortho and para state. Therefore to deduce λ_{OM} from λ_c , as indicated in Ref. [1], a correction has to be applied which can be approximated as follows:

$$\lambda_{OM} = \lambda_c (1 + K \lambda_{OP}/\lambda_0). \quad (2)$$

The value of K depends on the experimental conditions.

Moreover, in this case the capture neutron yield $N(t)$ is no longer exponential but, starting at $p\mu p$ formation time, can be shown to be,

$$N(t) \propto e^{-t/\tau_{\mu^-}} \left[1 + (\lambda_{OM} - \lambda_{PM})/\lambda_{PM} e^{-\lambda_{OP}t} \right]. \quad (3)$$

Since the ratio $\lambda_{OM}/\lambda_{PM}$ is known to be very close to 2.5 (owing to the V-A character of the interaction) a measurement of the neutron yield $N(t)$, knowing τ_{μ^-} , will give the value of λ_{OP} . We present here the results of such a measurement. Preliminary results were already presented at the Vancouver Conference in 1979 [8].

The muon beam and the ultra-pure hydrogen target used are those described in Ref. 1, and the problem of impurities, including deuterium, has already been discussed [1,9]. The muons are stopped in the target during the 3 μ s beam bursts of the Saclay Linac: the measurements of the yield $N(t)$ start 0.7 μ s after the end of the burst in a 60 μ s wide gate G. The capture neutrons (energy: 5.2 MeV) are detected in a set of 6 cylindrical ($\emptyset = 15$ cm, $L = 10$ cm) liquid scintillators N (NE 213). A sheet of plastic scintillators E (5 mm thick) surrounds the target in order to veto or detect the muon-decay electrons. A necessary condition for an event to be defined as a neutron is the requirement $\bar{N}\bar{E}$.

About 30% of the muon-decay electrons, radiating in the target walls, are not vetoed by E. The ratio of these $\bar{N}\bar{E}$ bremsstrahlung photons to the detected capture neutrons is about 3000. Therefore the rejection of these photons is quite essential. Two techniques are employed, using the shape of the phototube pulses. First (PSD1) the prompt and delayed components of the pulse are compared in two 100 ns wide gates with 0 and 40 ns delays, respectively. Second (PSD2) a discrimination is made from the rise-time of the integrated pulse (ORTEC circuit). Both techniques have a rejection factor of better than 10^5 against photons, for isolated events. However, any distortion in the pulse tails due to pile-up of small-energy photons reduces the rejection factor. The resulting fake neutrons have a mean lifetime: $\tau_{\mu-}/2$. Such a type of pile-up events are even much more frequent in the NE events (these events are mainly due to the radiating μ -decay electrons and therefore are expected to have the $\tau_{\mu-}$ lifetime) and will affect their observed lifetime.

Experimentally we found that the PSD1 and the PSD2 responses are different for the pile-up events allowing their almost total discrimination in a PSD1, PSD2 plane. The residual pile-up events in the region 1 (see Fig. 1) of the $\bar{N}\bar{E}$ capture neutrons are obtained from the number of pile-up events in the region 3: the coefficient of extrapolation is chosen in order to restore, with the same treatment, the expected lifetime $\tau_{\mu-}$, for the NE events.

In order to avoid any possible additional distortions in the capture neutron time distribution two other types of events are also rejected: a) Single events in the gate G preceded by a large pulse (more than 10 MeV) occurring within 5 μ s before G. b) Any second $\bar{N}E$ or NE event occurring during the gate G, which produces distortions in the neutron time distribution. About 45,000 neutron-like events $\bar{N}E$ have been taken for a threshold of 1 MeV on the recoil proton's energy. During the data taking the rate in each counter N was less than 0.1/gate.

After the $\bar{N}E$ neutrons have been isolated from the photons by accepting a small region of the PSD1-PSD2 plane (Fig. 1), the following background components are still to be subtracted:

- i) Neutrons due to cosmic-rays, measured in the late part of the gate G.
- ii) Residual pile-up events subtracted as explained before.
- iii) Fast delayed neutrons, still present in the experimental room, during the gate G. They are measured in runs with an empty target.
- iv) Photoneutrons, which are generated by photonuclear reactions inside and outside the neutron counters. After subtraction of neutron components i) to iii), the remaining neutrons NE and high-energy $\bar{N}E$ events (proton recoil energy more than 5.2 MeV) are photoneutrons. It is then possible to subtract the $\bar{N}E$ low-energy photoneutron component (less than 5.2 MeV -- region to which capture neutrons contribute) by assuming the same energy spectrum for $\bar{N}E$ and NE photoneutrons. A check was done by increasing the target-wall radiation length with an additional 2.5 mm lead sheet. Extrapolation to zero radiation length removes the photoneutrons. The two methods give the same photoneutron level.

As we are not interested in the absolute yield of capture neutrons, the optimum cut may be applied on the various parameters in order to minimize the background. Table 1 gives, for the various components, the number of neutrons in a 7 μ s wide gate, starting 1.5 μ s after the beam pulse and for a cut between 3 and 5 MeV on recoil proton energy.

The mean lifetimes are calculated by

$$\tau = \sum_i n_i t_i / \sum_i n_i + \varepsilon_K ,$$

the sum being extended up to 7 μ s, ε_K being the correction for the finite integration. For the capture neutrons, we finally find

$$\tau_n = (2084 \pm 30) \text{ ns} . \quad (4)$$

Figure 2 shows their energy spectrum, and their time distribution corrected for the μ^- decay factor $\exp(-t/\tau_{\mu^-})$.

The value of expression (4) is significantly smaller than $\tau_{\mu^-} = 2195 \text{ ns}$ [1]. The difference found between τ_n and τ_{μ^-} is interpreted as being due to a ppp ortho-para transition. Taking into account our experimental conditions, the corresponding value of λ_{OP} is:

$$\lambda_{OP} = (4.1 \pm 1.4) \times 10^4 \text{ s}^{-1} , \quad (5)$$

where the quoted error is mainly statistical. However, impurities could also simulate a small reduction of τ_n . We have checked that the lifetime of the high-energy ($> 5.2 \text{ MeV}$) $N\bar{E}$ neutrons $[(2290 \pm 110) \text{ ns}]$ is compatible with τ_{μ^-} . This allows us to set an upper limit on the possible effect of impurities of 40 ns. Moreover, it is shown, in Refs. [1] and [9], that the outgassing in the target as well as the filling procedure ensure an impurity concentration level smaller than 5×10^{-9} , corresponding to an effect on τ_n smaller than 6 ns. The value of expression (5) confirms our preliminary results [8,5].

In order to extract meaningful information from the experimental values of muon capture in liquid hydrogen, one must now take into account the value of Eq. (5). From our published value of $\lambda_c = (460 \pm 20) \text{ s}^{-1}$, using formula (2) with $K = (1.69 \pm 0.03)$ and the value of expression (5) for λ_{OP} , we deduce the following value for the orthomolecular muon capture rate:

$$\lambda_{OM} = (531 \pm 33) \text{ s}^{-1} . \quad (6)$$

In Table 2 are reported all experimental results [6,7,10-13] on muon capture in hydrogen and the corresponding values of the pseudoscalar coupling constant g_p^μ , assuming the usual standard hypothesis [14] together with the absence of second-class current^{*)}. We conclude with the following remarks as regards the results of Table 2:

- i) The average values for g_p^μ are obtained combining together all published (electronics) experiments: in particular using Eq. (5) one gets
$$g_p^\mu = 8.7 \pm 1.9.$$
- ii) The value of g_p^μ agrees with the PCAC prediction ($g_p^\mu = 8.4$) after the λ_{OP} correction is applied, but would disagree significantly if we assumed $\lambda_{OP} = 0$. On the other hand, assuming the theoretical value of PCAC, an upper limit can be deduced on the second-class current coupling constant g_t^μ : taking Eq. (5) one gets $g_t^\mu = 0.3 \pm 1.9$.

Acknowledgements

We are grateful to A. Mougeot and A. Godin for technical help. We are indebted to F. Netter and the ALS machine group operators for supplying the requested beams. One of us (E.Z.) thanks E. Gabathuler for his support. One of us (A.R.) is grateful, for partial support, to the Deutsches Bundesministerium für Forschung und Technologie. Finally, we wish to thank L.I. Ponomarev for useful discussions on the Dubna calculations.

^{*)} The value for the axial form factor $g_A^\mu(0) = (1.254 \pm 0.007)$ has been taken from Review of particle properties [15]: for the q^2 dependence correction, we have used the usual dipole correction with $m_A = 930 \pm 30$ MeV. For the Fermi coupling constant we have used $G = (1.16631 \pm 0.00002) \times 10^{-5} \text{ GeV}^{-2}$ resulting from our latest experimental determination of τ_{μ^+} in Ref. 1. For the Cabibbo angle we have taken the value given by Schrock and Wang [16]. The corrections due to the q^2 dependence of the vector form factors g_V^μ and g_M^μ have been calculated using the result given by Simon et al. [17].

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Table 1

Number of neutrons and lifetime of the different neutron components for events with proton recoil energy between 3 and 5 MeV, the events being chosen 1.5 μ s after the end of the 3 μ s pulsed muon beam.

	Component	Number of events	Lifetime (μ s)
a	Total	26746	
b	Cosmics	1915	∞
	Pile-up	96	2.195/2
	Copper	29	0.165
c	(a - b)	24706	2.079 ± 0.019
d	Empty target	2588	1.849 ± 0.095
	Photoneutrons	4388	2.195
e	Capture neutrons (c - d)	17730	2.084 ± 0.030

Table 2

Experimental results on muon capture in hydrogen and deduction of the pseudoscalar coupling constant g_p^μ . For the case of μ^- stopped in liquid hydrogen the values of λ_{OP} assumed are shown at the top of the column.

No.	Group	Target H ₂	Capture rate (s ⁻¹)	$g_p^\mu = -m_\mu f_p (-0.88 m_\mu^2)$	
				$\lambda_{OP} = 0$	$\lambda_{OP} = (4.1 \pm 1.4) \times 10^4 \text{ s}^{-1} \text{ a)}$
1	Chicago [10]	Bubble chamber (n) b)	428 ± 85	19.6 ± 8.4	17.7 ± 8.9
2	CERN-Bologna [11]	Bubble chamber (n) b)	450 ± 50	17.3 ± 5.1	15.4 ± 5.1
3	Columbia I [6]	Liquid (n) b)	515 ± 85	8.6 ± 7.9	6.0 ± 8.0
4	Columbia II [7]	Liquid (n) b)	464 ± 42	13.4 ± 4.2	11.0 ± 4.3
5	SCB [1]	Liquid (e) b)	460 ± 20	13.8 ± 2.0	7.1 ± 3.0
6	DUBNA [13]	Gas (n) b)	686 ± 88	7.9 ± 5.9	
7	CERN-Bologna [11]	Gas (n) b)	651 ± 57	10.3 ± 3.9	
Average 3-7				12.6 ± 1.5	8.7 ± 1.9

a) Present experimental result.

b) n = neutron and e = electron are the detected particles.

Figure captions

Fig. 1 : Distribution of the $N\bar{E}$ events in the PSD1-PSD2 plane. The neutrons (1) are in the central region, the gamma-rays (2) in the lower left corner, and the pile-up events (3) are scattered over all the plane.

Fig. 2 : a) Energy spectra (proton scale and electron scale): 1) sum of the background events; 2) capture neutrons, background subtracted.
b) Time distribution of the capture neutrons. The number of events in each time interval has been multiplied by $\exp(t/\tau_{\mu^-})$ to remove the time-dependence characteristic of the μ^- -decay electrons.
Curve 1 corresponds to $\lambda_{OP} = 0$ and curve 2 to $\lambda_{OP} = 4.1 \times 10^4 \text{ s}^{-1}$.

Fig. 1

Fig. 2