Detection of hot muonic hydrogen atoms emitted in vacuum using X-rays

R. JACOT-GUILLARMOD
Université de Fribourg, Chemin du Musée 3, CH-1700 Fribourg, Switzerland

J.M. BAILEY
University of Liverpool, P.O Box 147, Liverpool L69 3BX, UK

G.A. BEER, P.E. KNOWLES, G.R. MASON and A. OLIN
University of Victoria, Finnerty Road, Victoria, B.C. V8W 2Y2, Canada

J.L. BEVERIDGE and G.M. MARSHALL
TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C. V6T 2A3, Canada

J.H. BREWER and B.M. FORSTER
University of British Columbia, 6224 Agricultural Road, Vancouver, B.C. V6T 2A6, Canada

T.M. HUBER
Gustavus Adolphus College, St. Peter, MN 56082, USA

P. KAMMEL and J. ZMESKAL
IMEP, Austrian Academy of Sciences, Boltzmanngasse 3, A-1090 Wien, Austria

A.R. KUNSELMAN
University of Wyoming, Laramie, WY 82071, USA

C. PETITJEAN
Paul Scherrer Institute, CH-5232 Villigen, Switzerland

Abstract. Negative muons are stopped in solid layers of hydrogen and neon. Muonic hydrogen atoms can drift to the neon layer where the muon is immediately transferred. We found that the time structure of the muonic neon X-rays follows the exponential law where the rate is the same as the disappearance rate of μ^-p atoms. The ppμ-formation rate and the muon transfer rate to deuterium are deduced.

1. Introduction

By slowing down via Coulomb interaction with atomic and molecular electrons, muons are stopped in a layer of hydrogen at 2.5 K containing a small amount of deuterium. The μ^-p can disappear by muon decay, ppμ-mesomolecular formation or muon transfer to deuterium.

After the charge exchange reaction μ^-p+ d $\rightarrow$ μ^-d+ p, the muonic deuterium atom has a kinetic energy of about 45 eV. It is then slowed down to a few eV (Ramsauer-Townsend effect) by elastic scattering on protons.

The emission of these "hot" μ^-d atoms in vacuum has been extensively studied in terms of deuterium concentration and layer thickness dependences [1]. Because of their high velocity ($\sim$ 1 cm/μs), the μ^-d can drift a few centimeters away from the hydrogen layer before muon decay occurs. Therefore the decay e^- imaging system (DEIS) is a very convenient device for studying this process. The velocity of residual μ^-p atoms should be very low ($\sim$ 0.1 mm/μs) compared to the μ^-d's, but this type of emission cannot be completely excluded. This can however not be studied by using the DEIS because of its unsufficient spatial resolution.

To study the specific emission of μ^-p and μ^-d atoms we need another technique. The method is to freeze a neon layer on the surface of hydrogen. Muonic hydrogen atoms emitted in this direction will instantaneously release their muon and induce the formation of an excited muonic neon atom. Characteristic X-rays will be emitted and observed with a germanium detector.

The yield of muonic hydrogen emission (μ^-p and μ^-d) outside the layer (neglecting the drift time) is :

$$\frac{dN}{dt}(t) \propto N_{\mu p}(t) \propto e^{-\lambda t}$$

with

$$\lambda = \lambda_0 + (1 - c_d)\lambda_{pp\mu} + c_d\lambda_{pd} \qquad (1)$$

where $N_{\mu p}(t)$ is the number of remaining μ^-p atoms at time t, and λ their total disappearance rate.

2. Measurement

The experimental apparatus is shown in Fig. 1. The target preparation was made by first freezing the hydrogen on the gold foil and measuring the μ^-d emission with the DEIS. Simultaneously, the X-rays were observed to identify the presence of impurities, if any. Then, neon was added on the hydrogen layer surface.

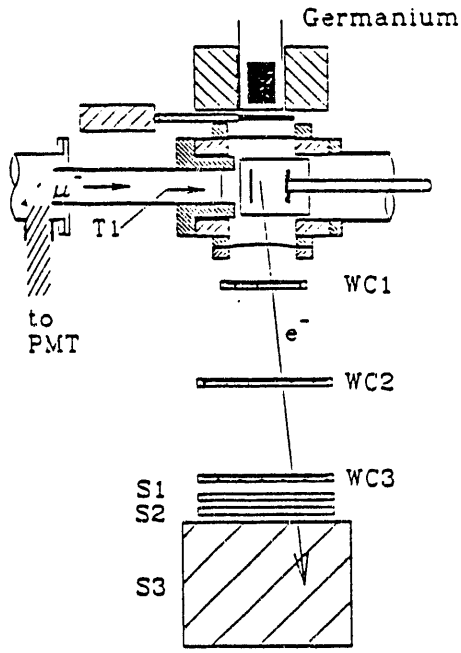

Figure 1: Experimental apparatus

This technique was applied for three targets presented in Table 1.

Table 1: Composition of the three targets. The $\oplus$ sign indicates that the neon is frozen on the hydrogen surface and not mixed. 1000 torr $\cdot$ l H_2 is 4.2 mg $\cdot$ cm^{-2}.

Target #	Composition		
I.	1506 torr $\cdot$ l H_2	$\oplus$	194 torr $\cdot$ l Ne
II.	1454 torr $\cdot$ l (H_2 + 145 ppm D_2)	$\oplus$	193 torr $\cdot$ l Ne
III.	725 torr $\cdot$ l (H_2 + 1150 ppm D_2)	$\oplus$	175 torr $\cdot$ l Ne

3. Data analysis

The total energy spectra obtained with a natural isotopic concentration of D_2 (target II), before (2a) and after (2b) the neon layer deposition is shown in Fig. 2. The absence of low Z element X-rays in Fig. 2a, and especially those from neon, indicates

clearly that the impurity contamination in hydrogen is negligible. Most of the neon line intensity of Fig. 2b is due to μ^- stopping directly in the neon layer.

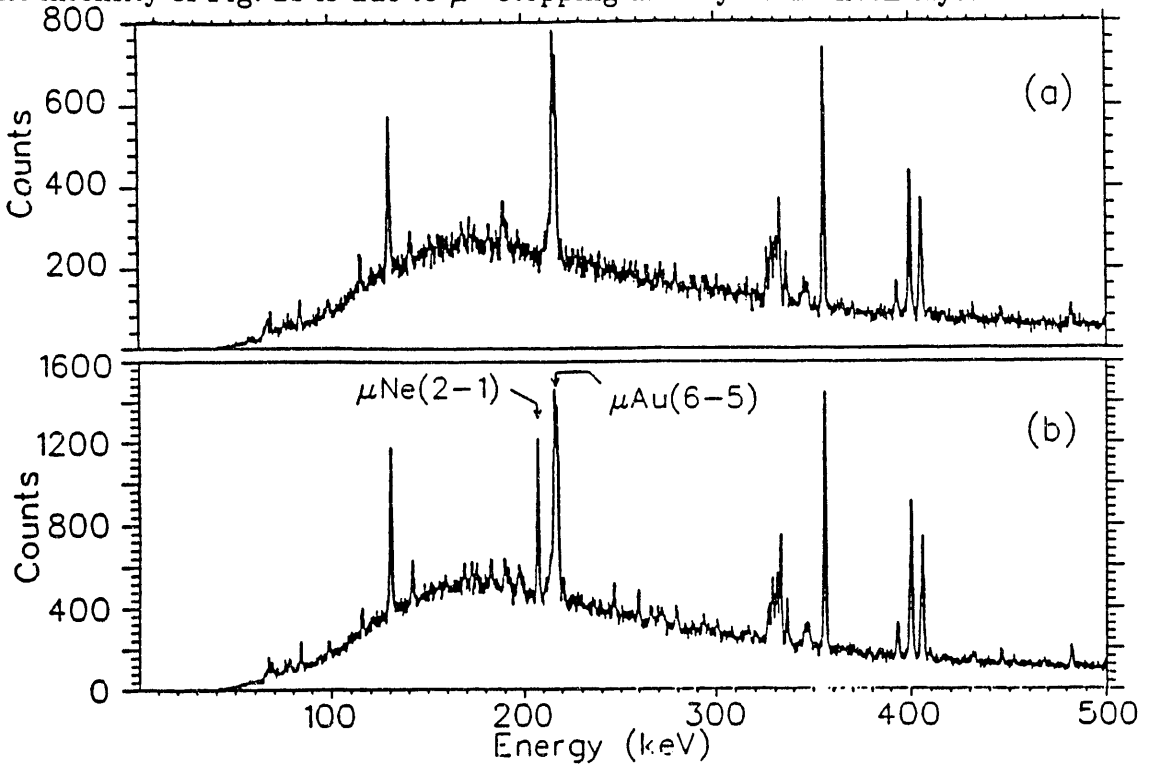

Figure 2: Part of the X-ray energy spectra without any time cut measured with target II (cf. Table 1). Upper (a) and lower (b) spectra have been obtained before and after neon deposition, respectively.

The specific contribution of the transfer process from muonic hydrogen can be observed by requiring a delayed time cut, as shown in Fig. 3 for the same data. It is essential to observe that the huge μAu(6-5) peak of Fig. 2 is then completely absent.

Table 2: Intensity of the μNe(2-1) line measured for different time cuts. By assuming an exponential dependence of the delayed intensities, the lifetime $\tau = 1/\lambda$ of the μ^-p is deduced.

Target	c_d	μNe(2-1) intensity for each time cut					Lifetime
	(ppm)	Prompt	Del I	Del II	Del III	Del IV	τ (ns)
I	0	9116	170	260	246	33	303
		(125)	(42)	(37)	(33)	(33)	(40)
II	145	5032	228	311	171	27	210
		(91)	(34)	(32)	(26)	(24)	(21)
III	1150	7057	365	110	20		56
		(100)	(36)	(28)	(23)		(9)

The complete absence of the delayed muonic gold X-rays is *a priori* very intriguing

because one would expect that delayed muonic gold X-rays would be apparent after μ^-d emission in direction of the gold foil. The intensity of the muonic transition μAu(6-5) by direct μ^- stop is about twenty times more than via μ^- transfer, because the circular transitions are much more favoured for the former.

One can then state that the delayed muonic neon X-rays in Fig. 3 follow the emission of muonic hydrogen into the adjacent neon layer where muon transfer eventually occurs.

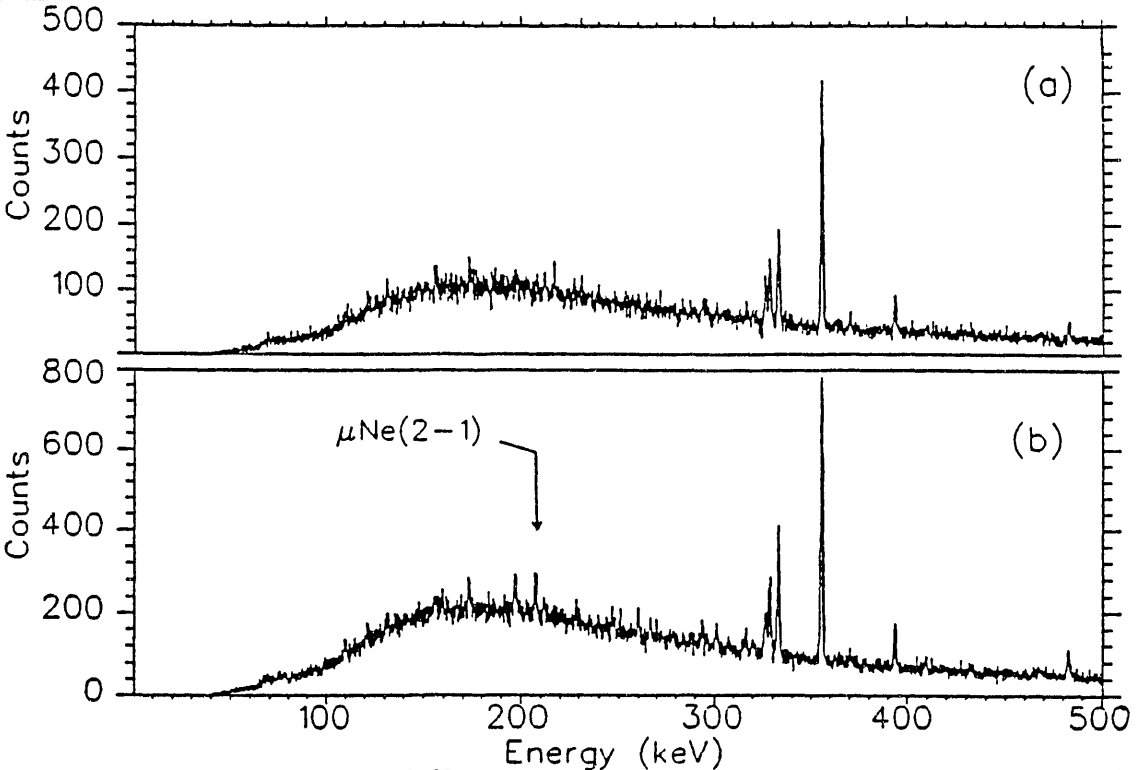

Figure 3: Part of the delayed X-ray energy spectra measured with target II (cf. Table 1). Upper (a) and lower (b) spectra have been obtained before and after neon deposition, respectively.

The counts of the μNe(2-1) line have been grouped in four time bins: from 40 to 120 ns after μ^- signal (this spectrum will be called Del I), from 121 to 339 ns (Del II), from 340 to 1539 ns (Del III) and from 1540 to 7931 ns (Del IV). The fitted intensities of μNe(2-1) in each time bin and the deduced lifetimes are reported in Table 2.

Using Eq. 1, one obtains a set of three linear equations, each one corresponding to one value of a deuterium concentration c_d, with two free parameters $\lambda_{pp\mu}$ and λ_{pd}. One finally gets :

$$\lambda_{pp\mu} = (2.18 \pm 0.32) \cdot 10^6 s^{-1}$$

$$\lambda_{pd} = (0.98 \pm 0.19) \cdot 10^{10} s^{-1}$$

These values are in fair agreement with those measured at comparable experimental conditions i.e. with liquid hydrogen during the sixties [2-4]. The rate λ_{pd} however differs from the value which is generally accepted for room temperature [5], $(1.68 \pm 0.26) \cdot 10^{10} s^{-1}$, although recent calculations [6] do not predict such energy dependence.

4. Acknowledgements

The support of the Natural Sciences and Engineering Research Council (NSERC) of Canada is gratefully acknowledged. One of us (R. J.-G.) wishes to thank the Swiss National Science Foundation for financial support.

References

[1] See G.M. Marshall *et al.* contribution in this volume.

[2] V.P. Dzhelepov, P.F. Ermolov, E.A. Kushnirenko, V.I. Moskalev, and S.S. Gershtein, Sov. Phys. JETP **15**, 306 (1962).

[3] E.J. Bleser, E.W. Anderson, L.M. Lederman, S.L. Meyer, J.L. Rosen, J.E. Rothberg, and I-T. Wang, Phys. Rev. **132**, 2679 (1963).

[4] G. Conforto, C. Rubbia, E. Zavattini, and S. Focardi, Il Nuovo Cim. **33**, 4281 (1964).

[5] A. Bertin, M. Bruno, A. Vitale, A. Placci, and E. Zavattini, Phys. Rev. **A7**, 462 (1973).

[6] C. Chiccoli, V.I. Korobov, V.S. Melezhik, P. Pasini, L.I. Ponomarev, and J. Wosniak, Muon Cat. Fusion **7**, 87 (1992).

END

DATE
FILMED
7/15/93