EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/79-73
6 July 1979

ISOTOPE EFFECT ON THE LYMAN SERIES OF μAl ATOMS
FORMED BY MUON TRANSFER FROM FREE μp AND μd SYSTEMS

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ABSTRACT

We have observed the Lyman series spectrum of μAl atoms formed through the transfer reaction $\mu\text{d} + \text{Al} \rightarrow \mu\text{Al} + \text{d}$. The results are compared with those previously obtained for the similar process $\mu\text{p} + \text{Al} \rightarrow \mu\text{Al} + \text{p}$.

(Submitted to Physics Letters A)

The muonic X-ray spectra ($X_{\mu p}$) from $\mu_Z Y$ atoms (where Z is the atomic number) formed through the muon transfer process

were investigated by several authors, for the case in which the reaction occurs from free muonic hydrogen (μp) atoms to ${}_Z Y$ elements in the gaseous [1] and in the solid [2] phase. For the elements studied ($Z_{\max} = 18$), it turned out that the higher members of the Lyman series of $\mu_Z Y$ atoms formed in this way are significantly enhanced with respect to the case of direct muon capture in the ${}_Z Y$ element.

However, this type of effect has so far not been studied for the case of the similar reaction

occurring from free muonic deuterium (μd) atoms to other elements; while it would be interesting to compare the $X_{\mu p}$ and $X_{\mu d}$ spectra following muon transfer from μp and μd systems to the same nucleus ${}_Z Y$ [3].

We report here the results of an observation of the Lyman series of μAl muonic atoms formed through reaction (2) (${}_Z Y$ now standing for Al), which will be compared with the Lyman spectrum measured by us [2] for μAl atoms formed through process (1). The data were taken at the 600 MeV CERN Synchro-cyclotron (SC2), during a series of measurements aimed at determining the elastic scattering cross-sections of μp and μd muonic atoms against protons [4] and deuterons. The muons were transferred from μd atoms -- formed in ultra-pure gaseous deuterium at 14 atm -- to a series of 30 μm thick, regularly spaced aluminium foils, immersed in the deuterium itself. The foils were covered by a natural layer of aluminium oxide (Al_2O_3 , 600 to 1000 $\text{\AA}$ thick) so that, owing to the high rate of process (2) [5], the muons transferred to the foils were totally captured by the Al_2O_3 layers [6]. The $X_{\mu d}$ radiation from

process (2) was identified by the technique of looking at the K-line^{*}) X-rays from μAl , coming after a suitable delay following the muon stopping time^{**}), and at the associated muon decay electrons [2,7].

Figure 1a shows the spectrum of the delayed X-rays, released in sequence to process (2), and observed [by means of two $3'' \times 3''$ NaI(Tl) detectors] within the energy range which is relevant to the Lyman series of the μAl atoms [$E(K_\alpha) = 347$ keV; the energy resolution was 13% FWHM for the K_α line]. The analysis of the spectrum in Fig. 1a was performed by a Monte Carlo program, which supplied the best-fitting distribution represented by the full line in the figure. The Monte Carlo calculation reconstructed the amplitude distribution of the signals from the NaI(Tl) detectors, taking into account the X-ray energies involved and the geometry of the apparatus [4].

For the relative K-line intensities corresponding to the spectrum of Fig. 1a, we obtained in this way

$$(K_\alpha/K_{\text{tot}})_{\mu\text{Al},d} = (0.59 \pm 0.13) \quad (3)$$

and

$$[(K_\beta + K_\gamma)/K_\alpha]_{\mu\text{Al},d} = (0.68 \pm 0.24) \quad (4)$$

From these results the following conclusions can be drawn:

- i) When μAl atoms are formed through the transfer process (2) from muonic deuterium to aluminium (bound in this case in Al_2O_3 molecules), the higher members of the Lyman series $X_{\mu d}$ are significantly enhanced with respect to the case of direct muon capture (see table 1) [8,9]. This is reported here for the first time for the case of a muon transfer process from free μd muonic atoms.
- ii) If the present result is compared to the one obtained for μAl atoms formed through process (1) [2] (see fig. 1 and table 1), it is clear that the relative

^{*}) The K-lines correspond to the $nP \rightarrow 1S$ Lyman series transitions (K_γ to $2P \rightarrow 1S$, K_β to $3P \rightarrow 1S$, and so on. Conventionally, the contribution of all $nP \rightarrow 1S$ transitions ($n \geq 4$) will be labelled here by K_γ ($K_{\text{tot}} = K_\alpha + K_\beta + K_\gamma$).

^{**}) The μd systems are electrically neutral, and have very small atomic dimensions ($a_\mu = 2.56 \times 10^{-11}$ cm). They attain the solid material after having diffused against the surrounding deuterium molecules.

enhancement of the $(K_{\beta} + K_{\gamma})$ lines appears less marked when the μAl systems are formed via muon transfer from muonic deuterium. In other words, the de-excitation to the ground level of μAl atoms formed by the transfer processes (1) and (2) shows different features according to the hydrogen isotope to which the muon was primarily bound.

- iii) Isotope effects on X-ray spectra from $\mu_Z\text{Y}$ muonic atoms, formed by stopping negative muons directly within hydrogen- and deuterium-containing compounds, were reported by Mausner et al. [3] and by Bergmann et al. [3], who interpreted them in terms of muon transfer processes within systems with bound hydrogen and deuterium. The measurements discussed in this letter were performed under physical conditions (free μd and μp atoms, mostly in their 1S ground state) where reactions (1) and (2) are expected to occur with more defined features [5] than in the case of hydrogen (deuterium)-containing molecules. However, the present results provide qualitative support to the interpretation advanced by these authors [3] and to the hydrogen isotope effect estimates given by them.
- iv) The results shown in fig. 1 would most likely be reproduced by an atomic cascade model where the initial angular momentum distribution of the transfer-generated μAl atoms are weighted to higher angular momentum states in the case of process (2) with respect to the case of process (1). Improved cascade calculations, in any case, should keep a significant account of the formation channels of the muonic atoms concerned.
- v) Experimental results on the $X_{\mu\text{p}}$ and $X_{\mu\text{d}}$ spectra from processes (1) and (2) are missing for $Z > 18$. We expect that systematic work in the region of high atomic number $_Z\text{Y}$ elements would also provide complementary information on these problems.

The authors are indebted to A. Sarti and G. Sicher for their continuous technical assistance, and to the CERN SC2 machine staff for friendly collaboration.

They also wish to thank E. Gabathuler for encouragement and support, and G. Fiorentini, S. Focardi and G. Torelli for some useful discussions.

Table 1

Measured relative intensity $[(K_\beta + K_\gamma)/K_\alpha]$ of the higher members of the Lyman series from μAl atoms formed through different processes ^{a)}.

Formation channel	Direct muon capture	Muon transfer from hydrogen isotopes	
		$\mu\text{d} + \text{Al} \rightarrow \mu\text{Al} + \text{d}$	$\mu\text{p} + \text{Al} \rightarrow \mu\text{Al} + \text{p}$
$[(K_\beta + K_\gamma)/K_\alpha]$	(0.19 ± 0.04) ^{b)}	(0.68 ± 0.24) ^{c)}	(1.22 ± 0.19) ^{d)}

a) These results refer to Al atoms bound in Al_2O_3 .

b) This value is obtained by combining the results given in references 8 and 9.

c) Result obtained in the present work.

d) See reference 2.

REFERENCES

- [1] Yu. G. Budyashov, P.F. Ermolov, V.G. Zinov, A.D. Konin and A.I. Mukhin, Yad. Fiz. 5 (1967) 599 [English translation: Sov. J. Nucl. Phys. 5 (1967) 426].
- G. Backenstoss, H. Daniel, K. Jentzsch, H. Koch, H.P. Powell, F. Schmeissner, K. Springer and R.L. Stearns, Phys. Lett. B56 (1971) 422.
- H. Daniel, H.J. Pfeiffer and K. Springer, Phys. Lett. A44 (1973) 447.
- H.J. Pfeiffer, K. Springer and H. Daniel, Nucl. Phys. A254 (1975) 433.
- [2] A. Bertin, F. Ferrari, I. Massa, M. Piccinini, G. Vannini and A. Vitale, Phys. Lett. A68 (1978) 201.
- [3] L.F. Mausner, J.D. Knight, C.J. Orth, M.E. Schillaci and R.A. Naumann, Phys. Rev. Lett. 38 (1977) 953.
- R. Bergmann, H. Daniel, F.J. Hartmann, J.J. Reidy and W. Wilhelm, *in Mesons in matter* (ed. V.H. Pokrovskij) (JINR, Dubna, 1977), pp. 156 ff.
- [4] A. Bertin, I. Massa, M. Piccinini, A. Vacchi, G. Vannini and A. Vitale, Phys. Lett. B78 (1978) 355.
- [5] See, for example, P.K. Haff, E. Rodrigo and T.A. Tombrello, Ann. Phys. 104 (1977) 363, and references therein.
- [6] A. Bertin, I. Massa, M. Piccinini, G. Vannini and A. Vitale, Nuovo Cimento Lett. 23 (1978) 401.
- [7] A. Bertin, I. Massa, M. Piccinini, G. Vannini and A. Vitale, Nuovo Cimento Lett. 21 (1978) 577.
- [8] A. Brandao d'Oliveira, H. Daniel and T. von Egidy, Phys. Rev. A13, (1976) 1772.
- [9] H. Daniel, H. Koch, G. Poelz, H. Schmitt, L. Tauscher, G. Backenstoss and S. Charalambus, Phys. Lett. B26 (1968) 281.

Figure caption

Fig. 1 : Energy distribution of the X-rays observed in the region of the Lyman series from μAl atoms formed by muon transfer processes:

a) Starting from free μd atoms (result obtained in the present work).

The arrows show the energies corresponding to the K_α and K_β lines.

The full curve represents the best fit obtained by the Monte Carlo calculation ($\chi^2 = 4$; number of points: 16).

b) Starting from free μp atoms (see reference 2).

Fig. 1