Comparison of muon and pion capture ratios in H_2-Ar gas mixtures

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The muonic Coulomb capture ratio $A(H_2,Ar)$ has been measured in two different H_2-Ar gas mixtures using two different methods of evaluation based on the muon transfer from hydrogen. The measured ratios agree with each other, but disagree with the corresponding pionic capture ratio and also with the ratios calculated from muonic and pionic $A(He,Ar)$ and $A(He,H_2)$ capture ratios. The large discrepancies might be related to unsolved problems in muon transfer.

For negative pions, a particular technique using the charge-exchange reaction, $p+\pi^- \rightarrow n+\pi^0$, allowed extensive measurements of per-atom capture ratios $A(H,Z)$ in hydrogen containing solid and liquid substances (see, e.g., Ref. 1 for a review) and in H_2-Z gas mixtures at high and low relative concentrations.[2] For muons, $A(H,Z)$ capture ratios cannot be measured by employing the usual x-ray or decay-electron techniques, because of the transfer of the muon from the μp atom to the element Z. One does not expect that the mechanism of formation of muonic atoms is strongly different from that of pionic atoms. However, a concentration dependence of the per-atom capture ratios in noble-gas mixtures has been observed for muons,[3] and the absence of such a dependence for pions in H_2-Z and ^{3}He-Z gas mixtures[4] is unexpected. With the exception of a lower limit for the per-atom capture ratio $A(H_2,He)$ for muons,[5] no other $A(H_2,Z)$ muon capture ratios have been measured.

The present paper reports on two measurements of the $A(H_2,Ar)$ muon capture ratio performed in two different H_2-Ar gas mixtures and using two different methods,[6] both based on the muon transfer.

A negative muon in a H_2-Ar gas mixture is captured by the Coulomb field of either an argon or a hydrogen nucleus. In argon, the muon capture occurs in a high atomic level n, and the promptly emitted muonic x-ray intensities from the Lyman series show a characteristic pattern. They can be reproduced by a calculation assuming a statistical angular momentum distribution.[7]

The muonic hydrogen atom formed by muon capture in a hydrogen nucleus deexcites promptly and gets thermalized under our experimental conditions of pressure and argon concentration[8] before it transfers its muon to an argon atom at a rate λ_{Ar}. The muon is transferred to an atomic level $n=12$ in argon, with low angular momenta favored.[8,9] The deexcitation of the $(\mu Ar)^*$ atom proceeds promptly after the muon transfer. The resulting muonic intensities of the Lyman series have a pattern and a time distribution which are characteristic of muon transfer.[8]

We assume that a μp atom can only disappear in a H_2-Ar gas mixture through free-muon decay, formation of $p\mu p$ molecules and transfer to argon with known rates λ_0, λ_{pp} and λ_{Ar}, respectively. Other disappearance channels can be neglected in our case. The total disappearance rate of the μp system can then be written as $\lambda=\lambda_0+\lambda_{pp}+\lambda_{Ar}$.

The experiment has been performed at the Paul Scherrer Institute (PSI) in Villigen (Switzerland). Details of the measurements and the data analysis are described in Ref. 8. The time resolution of the detection system for the muonic argon Lyman-series x rays was about 5 ns. The investigated H_2-Ar gas mixtures (a) and (b), had argon concentrations of $c_{Ar}=0.41\%$ and 2.02% ($c_{Ar}=n_{Ar}/n_{H_2}$ is the ratio of the number of argon atoms to the number of hydrogen molecules per unit volume in the H_2-Ar gas mixture), and total pressures of 9.6 and 14.9 bars, respectively. By taking for Λ_{Ar}, the transfer rate from hydrogen to argon reduced to the atomic density of liquid hydrogen, the mean value of $1.44(4)\times10^{11}$ s^{-1} (cf. Ref. 8), we obtain $\lambda_{Ar}=3.40\times10^6$ s^{-1} and 24.4×10^6 s^{-1} for the mixtures (a) and (b), respectively; the total disappearance rates λ are 3.88×10^6 and 24.9×10^6 s^{-1}, respectively.

We employed two different methods for the determination of the $A(H_2,Ar)$ capture ratio: in the first method, one uses the structure of the time distribution of the muonic x rays of the Lyman series, and in the second, one uses their intensity patterns.

The first method, or time structure method, has already been described in detail in another paper.[6] The function $f(t)$ representing the time resolution of our detection system can be reproduced by a Gaussian, as has been tested by measuring the time spectrum of the muonic K series in pure argon. The time distributions of the muonic argon $2p$-$1s$ x rays measured in the H_2-Ar gas mixtures (Fig. 1) can then be fitted with an analytic function of five parameters, namely, the position of the prompt peak, its full width at half maximum, the total number of prompt events, N_{Ar}, the disappearance rate of the μp atoms, λ, and the total number of delayed events, N_H. The net time spectra of the muonic Ar($2p$-$1s$) events

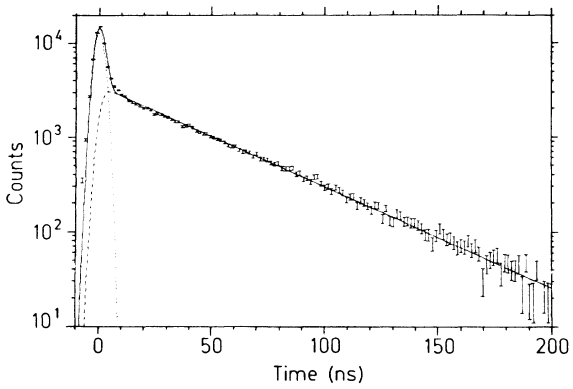

FIG. 1. Time distribution of the muonic Ar $2p$-$1s$ events measured in a H_2+(2.02% Ar) mixture at 14.9 bars. Dotted line: fitted function for direct capture. Dashed line: fitted function for transfer from hydrogen. Solid curve: total fitted function.

is obtained by subtracting the background events. If $I_d(2\text{-}1)$ and $I_t(2\text{-}I)$ represent the relative $I(2p\text{-}Is)/\sum I(np\text{-}1s)$ intensities of the muonic $K\alpha$ x rays in argon from direct muon capture and from transferred muons, respectively, the capture ratio $A(H_2,Ar)$ can be written as

$$A(H_2,Ar)=c_{Ar}\left[\frac{N_H}{N_{Ar}}\frac{\lambda}{\lambda_{Ar}}\frac{I_d(2\text{-}1)}{I_t(2\text{-}1)}\right]. \quad (1)$$

It is important to remark that Eq. (1) is practically independent of the stopping distribution and detector efficiency.

The second method, or intensity structure method, uses the principle that the muonic x-ray intensity structure of the argon Lyman series in a H_2-Ar gas mixture is a superposition of the intensity structures from direct muon capture in argon and from transferred muons to argon. Figure 2(a) shows this structure for pure transfer, measured in the H_2+(2.02% Ar) gas mixture, and Fig. 2(b) for direct capture measured in pure argon at 1.5 bars. One observes that the relative $I(np\text{-}1s)/I(2p\text{-}1s)$ intensities are strongly enhanced in transfer compared to direct capture. The numerical values listed in Table I show that this enhancement can exceed a factor of 10.

Table I also shows that the relative intensities $I(2p\text{-}1s)/\sum I(np\text{-}1s)$ measured in pure argon at 1.5 and 22 bars are practically the same. The electron refilling rate during the muonic cascade does not strongly change the muonic Lyman-series intensity patterns in this pressure range. One can therefore assume that the muon cascade following direct muon capture in argon of our H_2-Ar gas mixtures leads to the same relative $2p$-$1s$ intensities in pure argon.

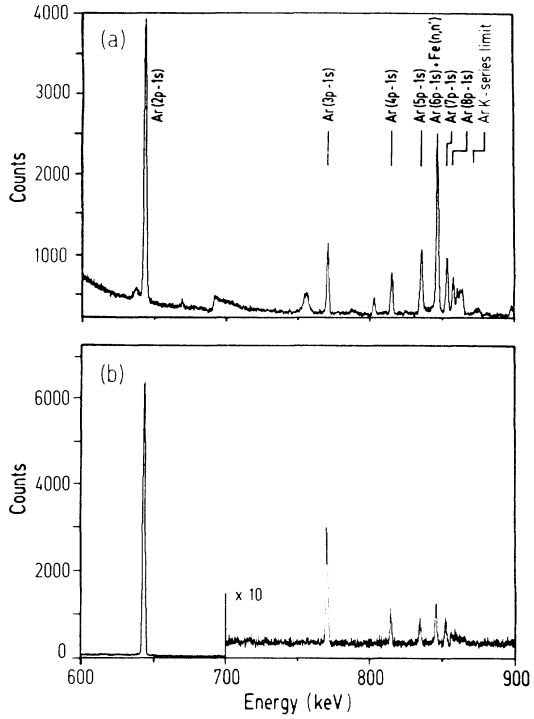

FIG. 2. Muonic Lyman series in argon by (a) transfer from hydrogen in a H_2+(2.02% Ar) mixture at 14.9 bars, (b) direct capture in pure argon at 1.5 bars.

Let D_n and T_n be the relative muonic intensities $I(np\text{-}1s)/I(2p\text{-}1s)$ in pure argon (direct muon capture) and in transfer to argon from the $1s$ state of the μp atom, respectively. The relative muonic intensities $S_n=I(np\text{-}1s)/I(2p\text{-}1s)$ measured in a H_2-Ar gas mixture are then a linear combination of D_n and T_n:

$$S_n=(1-\alpha_n)D_n+\alpha_n T_n\ , \quad (2)$$

where α_n is the fraction of muons transferred to argon from the μp atoms to the total number of captured

TABLE I. Relative intensities of the muonic Lyman series in argon after direct muon capture, after transfer from μp and in a H_2+(2.02% Ar) mixture.

Transition	Direct capture[a] 1.5 bars	Direct capture[a] 22 bars	Transfer[b]	H_2+(2.02% Ar) 14.9 bars
$2p$-$1s$	1000(30)	1000(30)	1000(7)	1000(4)
$3p$-$1s$	43.8(24)	45.2(16)	258(3)	217(2)
$4p$-$1s$	10.6(12)	12.8(9)	159(4)	136(2)
$(2p\text{-}1s)/\sum(np\text{-}1s)$	0.914(26)	0.905(25)	0.396(9)	

[a]Reference 7.
[b]Reference 8.

TABLE II. Muonic capture ratios $A(H_2,Ar)$ determined with the time structure and the intensity structure methods.

	Time structure c_{Ar}		Intensity structure $c_{Ar}=2.02\%$		
	0.41%	2.02%	$3p$-$1s$	$4p$-$1s$	Mean value
$A(H_2,Ar)$	0.094(8)	0.107(14)	0.085(18)	0.110(46)	0.096(7)

muons. The muon capture ratio $A(H_2,Ar)$ is then given by

$$A_n(H_2,Ar)=c_{Ar}\left[\frac{\alpha_n}{1-\alpha_n}\frac{\lambda}{\lambda_{Ar}}\right]=c_{Ar}\left[\frac{D_n-S_n}{S_n-T_n}\frac{\lambda}{\lambda_{Ar}}\right]. \quad (3)$$

The index n in A_n indicates that a capture ratio can in principle be determined from each individual relative intensity $I(np\text{-}1s)/I(2p\text{-}1s)$. Only for the $H_2+(2.02\%$ Ar) mixture was the statistics sufficient to apply the intensity structure method.

The measured capture ratios $A(H_2,Ar)$ obtained with the two methods are given in Table II. All four capture ratios agree with each other within the limits of the given uncertainties. Our four capture ratios are also compatible with the only other measured muonic capture ratio, $A(H_2,Ar)=0.12\pm0.03$, obtained from the figure of Ref. 10.

The mean muon capture ratio is, however, significantly different from the capture ratio measured for pions. Petrukhin and Suvorov[2] obtain $A(H_2,Ar)=0.172\pm0.005$ for pions, a ratio greater by more than 50% than the muon capture ratio. In He-Ar gas mixtures, on the other hand, the muonic and pionic capture ratios $A(He,Ar)$ are not in contradiction with each other, as can be seen from Table III. The same is true for the $A(He,H_2)$ capture ratios, although the pionic capture ratio is slightly higher than the theoretical predictions.[11] From the experimental capture ratios $A(He,Ar)$ and $A(He,H_2)$ given in Table III, one calculates a pion capture ratio of $A(H_2,Ar)=0.177$, which agrees with the pion capture ratio measured in the H_2-Ar gas mixture.[2] For the muon capture ratio, one obtains with the same procedure a lower limit for $A(H_2,Ar)\geq0.15$, which does not disagree with the corresponding pion capture ratio, but disagrees with our muon capture ratios (Table II).

TABLE III. Muonic and pionic capture ratios $A(He,H_2)$ and $A(He,Ar)$.

	$A(He,H_2)$		$A(He,Ar)$	
Author	Muon	Pion	Muon	Pion
Budyashov *et al.*[a]			0.148(10)	
Petrukhin *et al.*[b]		0.92(5)		0.161(10)
Hutson *et al.*[c]			0.208(39)	
Bannikov *et al.*[d]				0.165(29)
Cohen *et al.*[e] (theory)	0.73–0.79	0.71–0.76		
Kottman *et al.*[f]	<0.8 (2)			

[a]Reference 10. [d]Reference 4.
[b]Reference 2. [e]Reference 11.
[c]Reference 17. [f]Reference 5.

Our argon concentrations are very low compared to those used to determine the pion capture ratio ($0.01\leq c_{Ar}\leq2.0$) (cf. Ref. 2). One may envisage that the per-atom capture ratio changes monotonically with the concentrations of the components as predicted by Vogel *et al.*[12] and by Cohen *et al.*[11] In Ne-Ar gas mixtures, it has indeed been observed that the per-atom muon capture ratio $A(Ar,Ne)$ increased by about 30%, if the concentration n_{Ar}/n_{Ne} is increased by a factor of 16 at constant total pressure.[3] If, in our H_2-Ar gas mixtures with very low argon concentrations, there would be such a concentration dependence, we should measure a muon capture ratio $A(H_2,Ar)$ greater than the pion capture ratio. Obviously, the assumed concentration dependence does not explain the large difference between the pionic and muonic data.

In both our methods employed to determine the muonic $A(H_2,Ar)$ capture ratios, we assume that the muon transfer occurs only from the μp ground state. The transfer cross section from excited μp states is about 2 orders of magnitude larger than from the ground state.[13] For the time structure method, such events would appear as direct capture events in argon and decrease the $A(H_2,Ar)$ capture ratio. The same capture ratio determined by the intensity structure method would show the same decrease only if the muon transferred from excited μp states would give the same muonic Lyman-series intensity pattern as direct capture in argon, which is very improbable. In addition, at our very low argon concentrations, $c_{Ar}\cong1\%$, only the metastable $2s$ state of the μp atom has a lifetime sufficiently long so that the muon would have a chance to be transferred to argon. However, already the $2s$ population alone, which is estimated[14,15] to be about 8%, is too low to explain the small $A(H_2,Ar)$ capture ratio for muons.

Our measured capture ratios $A(H_2,Ar)$ are not only small compared to the pionic capture ratio, but also compared to model predictions, which generally yield values compatible with the experimental ones. The Fribourg version[16] of the mesomolecular model predicts a ratio of 0.25, which agrees with the capture ratio calculated from the $A(He,H_2)$ ratio of Kottmann[5] and the $A(He,Ar)$ ratio of Hutson *et al.*[17] (Table III).

We have no explanation for the important difference between muonic and pionic $A(H_2,Ar)$ capture ratios, nor for the inconsistency of the measured capture ratios with the ratio calculated from $A(He,H_2)$ and $A(He,Ar)$ ratios. However, our capture ratios are based on muon transfer, where already other inconsistencies have been observed.[8,18]

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