Charge Transfer from Muonic Hydrogen to Neon

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(Received 14 February 1990)

Fundamentally, the electron and muon transfer mechanisms are the same. We report on muon transfer from the ground state of muonic hydrogen to neon, measured in the gas mixtures H_2+Ne and H_2+Ne+Ar. Unexpectedly, the muonic x-ray time spectra measured in the binary mixture show two components. From the extracted transfer rates, the higher one agrees with an older experiment, whereas the lower one, which is reproduced in the triple gas mixture, was not observed before.

PACS numbers: 36.10.Dr, 34.70.+e, 82.30.Fi

The charge-transfer process between atoms or between atoms and ions is one of the most fundamental processes in atomic collisions and the basis for the understanding of chemical reaction mechanisms. Only very little is known about the charge-transfer process between atomic hydrogen and multicharged ions in collisions at thermal velocities.[1,2] Even if the length scales of ordinary and muonic hydrogen are very different, muon transfer and electron transfer are both charge-transfer phenomena.

The muonic hydrogen atom transfers its muon in collisions to any other atom. According to our present knowledge of the muon transfer mechanism, the collision partner of the muonic hydrogen atom can, in good approximation, be considered as a bare ion. Helium is an exception.[3] The experimental conditions can be chosen in such a way that the charge transfer occurs at thermal velocities from the ground state of the muonic hydrogen atom.[4,5]

A negative muon, stopped in a mixture of natural hydrogen with another gas of atomic number Z, forms a muonic hydrogen or a muonic Z atom in an excited state. In the deexcitation process by the Auger effect and radiation, muonic x rays are emitted which appear promptly with regard to the stopping muon. After deexcitation of the $(\mu p)^*$ atom, which occurs essentially by collisions with hydrogen molecules if the concentration of the admixed gas is small, the (μp) atom is in the ground state, after less than about 10^{-9} s at a pressure of about 10 bars.[6] The $(\mu p)_{1s}$ atom can then disappear by muon decay with an associated rate λ_0, by formation of a $(p\mu p)$ mesomolecule (λ_{pp}), or by transferring the muon to deuterium (λ_d) or to element Z (λ_{pZ}). The total disappearance rate of the (μp) atom, λ, is then

$$\lambda=\lambda_0+\lambda_{pp}+\lambda_d+\lambda_{pZ}\,. \tag{1}$$

The transfer of the muon from the $(\mu p)_{1s}$ atom occurs to much lower atomic levels compared to direct capture in the Z atom, and the associated angular momentum distribution is also very different, such that the muonic x-ray intensity pattern, resulting from transferred muons, is characteristic for the charge-transfer process.[5,7] These muonic x rays, emitted promptly after muon transfer, are delayed relative to a muon stop in the gas, and their time distribution is expected to be an exponential function with the disappearance rate λ as the characteristic decay constant. $\tau=1/\lambda$ is then the lifetime of the (μp) atom in the ground state.

In previous experiments, where we measured the muon transfer rate from muonic hydrogen to argon and helium,[4,5] the measured time distributions of the delayed muonic x rays in argon corresponded, as expected, to a single exponential function. In another experiment, where we investigated the charge transfer from muonic hydrogen to sulfer dioxide,[8] we observed the expected exponential time distribution in the muonic sulfur x rays, but an unexpected double exponential structure in the muonic oxygen x rays.

In the present paper, we report on muon transfer from muonic hydrogen atoms in the ground state to neon, measured at room temperature in two gas mixtures at a pressure of 15 bars: H_2+0.69% Ne and H_2+0.14% Ne+0.14% Ar. The noble-gas concentrations are molecular ratios. The experiments have been performed at the Paul Scherrer Institute (PSI) in Villigen. The experimental setup, the peak-to-background ratios, the background subtraction, and the data analysis were comparable to preceding measurements.[5,8]

In the measurement of the time distributions of the muonic x rays in the H_2+0.69% Ne mixture, our first surprise was the unexpectedly high lifetime of the (μp) atom. Starting from the transfer rate measured by Alberigi Quaranta *et al.*,[9] we expected to measure under our experimental conditions a lifetime of about 130 ns.

TABLE I. Fitted decay times in the muonic neon Ne(n-1) time spectra, measured in the H_2+0.69% Ne gas mixture at 15 bars.

Transitions	τ_1 (ns)	τ_2 (ns)
Ne(2-1)	127(24)	1087(28)
Ne(3-1)	144(60)	1111(100)
Ne(4-1) to Ne(6-1)	156(53)	1089(50)
Mean value	133(21)	1089(24)

The analysis of the time distributions of the muonic Ne(2-1), Ne(3-1), and Ne(4-1) to Ne(6-1) x rays gave lifetimes of more than a microsecond (Table I). The second surprise was to need two exponential functions to obtain good fits of the time spectra. All three time spectra (Fig. 1) showed the same characteristics with compatible time constants (Table I). The average lifetimes deduced from the flatter and the steeper slopes were 1089(24) and 133(21) ns, respectively. The number of muonic neon x-ray events corresponding to the shorter lifetime was about 4% of the delayed events of the neon Lyman series.

The measured exponential decays are not due to hidden nuclear transitions, to background, or to an electronic malfunction of the detection system. These possibilities were tested by measuring the time spectra of the muonic x rays in a mixture of neon and argon. The Gaussian time distribution of the muonic neon x rays measured in this gas mixture without hydrogen indicated clearly that the transitions were prompt, as expected. Hence the two decay components found in the H_2 +0.69% Ne mixture are related to the presence of hydrogen. In our opinion, we are seeing unknown processes similar to those observed in H_2+SO_2 two years ago.[8] It is worthwhile to notice that both processes induce the same muonic Lyman-series intensity pattern as is expected for muon transfer from muonic hydrogen in the ground state.

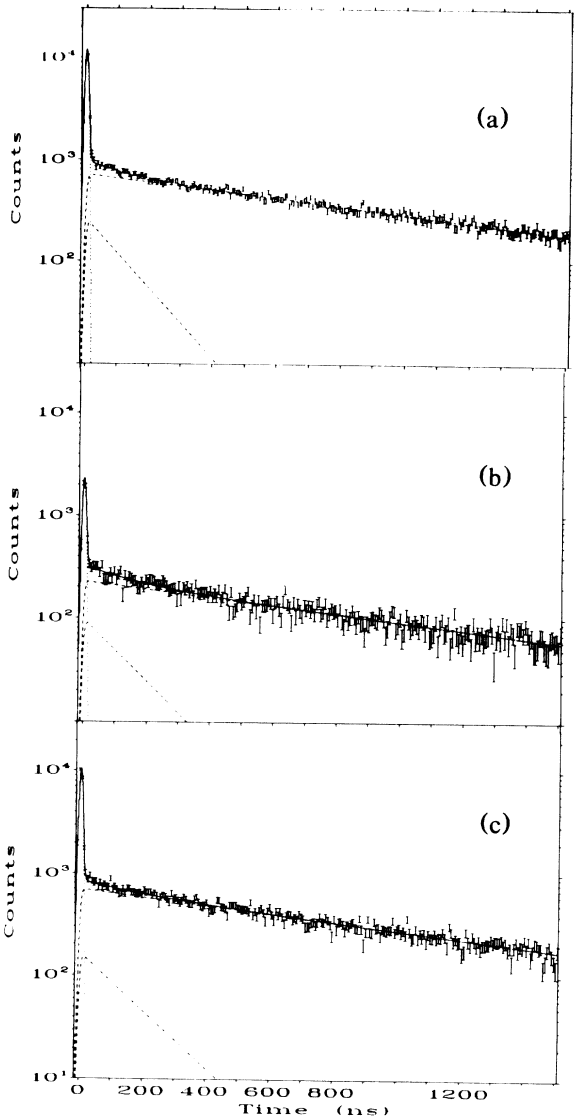

FIG. 1. Time distributions of muonic neon np-1s x-ray events, measured in the binary gas mixture H_2+0.69% Ne at 15 bars. The continuous line represents the fits to the data, the dashed and dotted lines the contributions of the components. (a) Ne(2-1), (b) Ne(3-1), (c) sum of Ne(4-1), Ne(5-1), and Ne(6-1).

From the measured decay rates λ, one can calculate, using Eq. (1), the experimental transfer rate from muonic hydrogen to element Z, λ_{pZ}, the other rates being known. To compare it with other experimental values measured at different pressures and concentrations, one normalizes them to the atomic density of liquid hydrogen ρ_0. The normalized transfer rate, Λ_{pZ}, is then

$$\Lambda_{pZ}=(\rho_0/N_Z)\lambda_{pZ}\,, \tag{2}$$

where N_Z is the atomic density of element Z. By using natural hydrogen, transfer to the element Z also occurs from the muonic deuterium atom (μd). Because of the low values of the concentration and of the normalized transfer rate to deuterium compared to other elements ($\Lambda_d=0.17\times10^{11}$ s^{-1}), the transfer from (μd) atoms can be treated as a correction.[5]

Our third surprise was to see that the normalized transfer rate Λ_{pZ}, deduced from the shorter mean time constant, corresponds exactly to the value of Alberigi Quaranta *et al.*,[9] and that the other transfer rate is about a factor of 20 less, i.e., even a factor of 2 less than the transfer rate to deuterium. Alberigi Quaranta *et al.* used, however, the triple-gas-mixture method (H_2 +0.58% Ne+0.12% Xe at 26 bars), and their technique of analysis was based on intensities and differed, therefore, from ours.

Conforto *et al.*,[10] who used the same technique, have measured the transfer rate to neon in liquid H_2. They found only one decay component and a transfer rate, $\Lambda_{p\mathrm{Ne}}=0.28\times10^{11}$ s^{-1}, which is surprisingly low compared to the corresponding transfer rate from deuterium[10] and to the transfer rate measured by Alberigi Quaranta *et al.*[9]

In the triple gas mixture H_2+Ne+Ar, the time spectra of the muonic Ar(2-1), (3-2), (4-2), (5-2), (6-2), and Ne(2-1) x rays have been analyzed (Fig. 2). From the mean lifetime $\tau=428(4)$ ns, the normalized muon transfer rate from muonic hydrogen to neon was deduced, $\Lambda_{p\mathrm{Ne}}=0.056(48)\times10^{11}$ s^{-1}, assuming a normalized transfer rate to argon $\Lambda_{p\mathrm{Ar}}=1.44(4)\times10^{11}$ s^{-1}, obtained from previous experiments.[5] The great uncertainty on $\Lambda_{p\mathrm{Ne}}$ is due to the low contribution of only 3% of

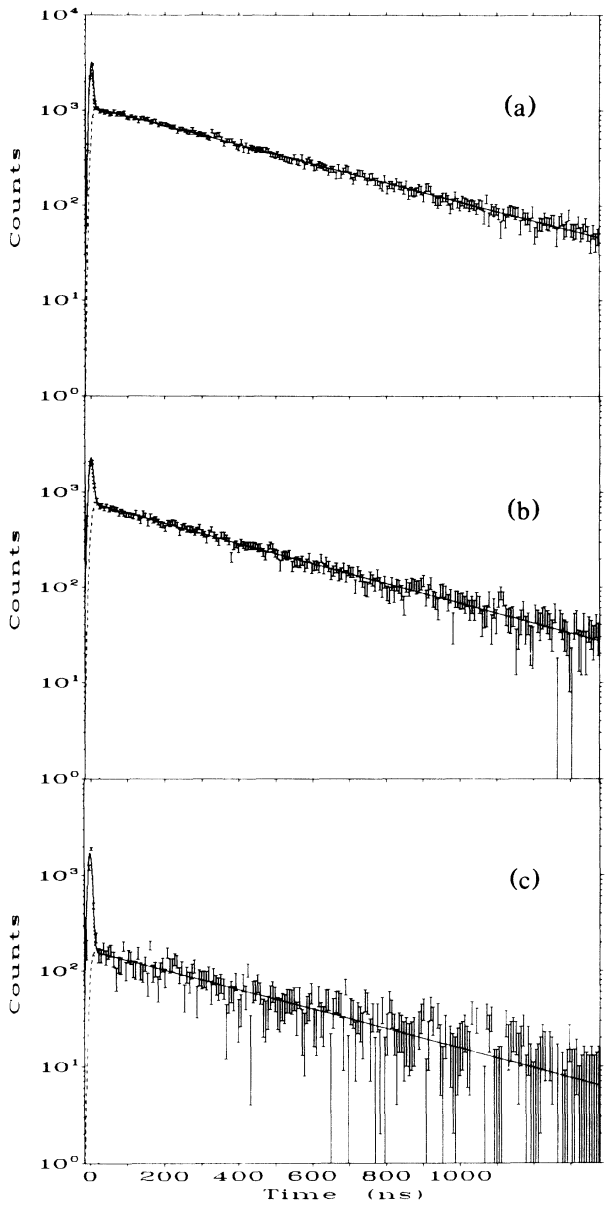

FIG. 2. Measured and fitted time distributions of muonic x-ray events, measured in the triple gas mixture H_2+0.14% Ne+0.14% Ar at 15 bars. (a) Ar(2-1), (b) Ar(3-2), (c) Ne(2-1).

$\lambda_{p\mathrm{Ne}}$ to the total disappearance rate λ. This transfer rate $\Lambda_{p\mathrm{Ne}}$ agrees with the one deduced from the binary mixture H_2+0.69% Ne. One exponential sufficed to fit all the time spectra well. The statistics of the time spectrum of Ne(2-1) was, however, too poor to observe a 4% intensity effect, comparable to the one observed in H_2 +0.69% Ne.

The ratio of the normalized transfer rates, $\Lambda_{p\mathrm{Ne}}/\Lambda_{p\mathrm{Ar}}$, should correspond to the ratio of the per-atom captured muons via transfer, A_t(Ne/Ar), from (μp) atoms in the ground state (Fig. 3). By taking into account the correc-

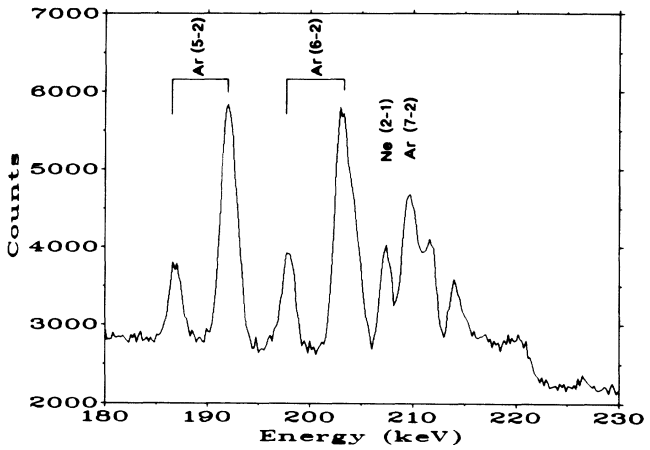

FIG. 3. Part of the delayed muonic x-ray spectrum, measured in the triple gas mixture H_2+0.14% Ne+0.14% Ar at 15 bars, containing part of the Balmer-series transitions in Ar and the Lyman series in Ne.

tions due to transfer from the (μd) atoms, the formula

$$\Lambda_{p\mathrm{Ne}} = \left(\Lambda_{p\mathrm{Ar}} + \Lambda_{d\mathrm{Ar}}\frac{\lambda_d}{\lambda'}\right) A_t \left(\frac{\mathrm{Ne}}{\mathrm{Ar}}\right) - \Lambda_{d\mathrm{Ne}}\frac{\lambda_d}{\lambda'} \qquad (3)$$

allows us to calculate the normalized transfer rate from muonic hydrogen to neon using the intensity method. Here $\lambda' = \lambda_0 + \lambda_{pd} + \lambda_{d\mathrm{Ne}} + \lambda_{d\mathrm{Ar}}$ is the disappearance rate of the (μd) atom under experimental conditions [λ_{pd} is the formation rate of $(p\mu d)$ molecules]. $\Lambda_{d\mathrm{Ar}} = 0.72 \times 10^{11}\ \mathrm{s}^{-1}$ and $\Lambda_{d\mathrm{Ne}} = 1.42(20) \times 10^{11}\ \mathrm{s}^{-1}$ have been measured by Placci *et al.*[11] The muon transfer rate from muonic hydrogen to neon, determined through the intensity method in this triple gas mixture, $\Lambda_{p\mathrm{Ne}} = 0.062(4) \times 10^{11}\ \mathrm{s}^{-1}$, is in perfect agreement with the one obtained in the binary mixture H_2+0.69% Ne, and about 20 times less than the one obtained by Alberigi Quaranta *et al.* using the same methods with xenon instead of argon. This result of the x-ray intensity evaluation in the triple mixture rules out the possibility of metastable states populated after transfer. The comparison of the different $\Lambda_{p\mathrm{Ne}}$ rates is given in Table II.

In both gas mixtures, the intensity patterns of the

TABLE II. Comparison of normalized muon transfer rates $\Lambda_{p\mathrm{Ne}}$ measured in gaseous mixtures at room temperature, with indication of the method employed (for other details, see text).

Authors	Method	Mixture	$\Lambda_{p\mathrm{Ne}}$ ($10^{11}\ \mathrm{s}^{-1}$)
Alberigi Quaranta *et al.*	a	H_2+Ne+Xe	1.16(28)
This work	b	H_2+Ne	1.15(20)
This work	b	H_2+Ne	0.062(4)
This work	b	H_2+Ne+Ar	0.056(48)
This work	a	H_2+Ne+Ar	0.062(5)

[a]Intensity method.
[b]Time structure method.

muonic Lyman-series x rays, which appear delayed with respect to a stopping muon, have the same characteristics as would result from muon transfer from the ground state of (μp) atoms. If the observed decay times were due to unknown processes, the intensity structure of the delayed x rays would not allow us to distinguish them from the known charge-transfer process.

The double decay time, observed in the muonic neon x rays in the H_2+0.69% Ne gas mixture, is particularly puzzling. From the shorter, 4% component, assumed to proceed from muon transfer, one deduces a normalized transfer rate $\Lambda_{p\mathrm{Ne}}$ which is exactly equal to the normalized transfer rate, observed twenty years earlier at CERN. To the main component corresponds a 20-times-smaller transfer rate $\Lambda_{p\mathrm{Ne}}$, which is well reproduced in the triple gas mixture whether one employs the method of the time structure or that of the intensity ratio for the analysis.

In electron transfer measurements from molecular hydrogen to stored O^{2+} ions, Church and Holzscheiter[12,13] also observed single and double exponential decay times of the O^{2+} ions. Their situation is, however, not comparable to ours in all details.

The comparison of muon and electron transfer rates does not yet help to interpret the surprising phenomena observed in muon transfer. However, the double decay rates, observed in the mixture of hydrogen with a noble gas, H_2+0.69% Ne, confirm that those observed in oxygen of H_2+SO_2 are not due to some unknown "chemical" effect.[8] The fact that the transfer rate $\Lambda_{p\mathrm{Ne}}$, measured twenty years ago at CERN, is reproduced and that the second transfer rate, the very low one, is reproduced in the triple gas mixture, seems to raise the same questions as the transfer rates to argon.[14]

The authors would like to thank L. A. Schaller and L. Schellenberg for their help during the data-taking period. They are indebted to W. Reichart, who wrote the data-acquisition program DAVID used in these measurements. The authors thank L. I. Ponomarev, G. Torelli, and E. Zavattini for useful discussions. The present work was supported in part by the Swiss National Science Foundation.

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