Muon transfer from hydrogen and deuterium atoms to neon

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The muon exchange reactions from the ground state of muonic protium and deuterium atoms to neon are studied. Measurements have been performed in binary gas mixtures at room temperature. The transfer rate from thermalized muonic deuterium is found to exceed by about an order of magnitude the one from muonic protium. On the other hand, an energy dependence of the rate from μd is revealed, while none is observed from μp. The intensity patterns of the muonic Lyman series of neon resulting from the muon exchange differ from one hydrogen isotope to the other, the most obvious discrepancy being the presence of the muonic Ne(7-1) line after transfer from μd, whereas this line is absent by transfer from μp. This indicates that the muon is transferred to the level $n_p = 6$ in neon from protium, respectively, $n_d = 7$ from deuterium. This observation disagrees with the theoretical predictions. This study sheds some light on the surprising behavior of muon transfer to neon.

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I. INTRODUCTION

The study of the muon exchange from hydrogen to elements with higher atomic charge is not a recent field of investigation. It started about 30 years ago, along with the first predictions made by Gershtein [1] for the yields of these reactions. Among other elements, the case of neon was especially interesting, because of the thermodynamic properties of this element, which made it suitable for investigation in liquid hydrogen bubble chambers [2–4].

The overall disappearance yields of the muonic hydrogen and deuterium atoms were measured, and the intrinsic yields $\Lambda_{p\mathrm{Ne}}$ and $\Lambda_{d\mathrm{Ne}}$, usually called *transfer rates*, of the reactions

$$\mu x + \mathrm{Ne} \rightarrow \mu\mathrm{Ne} + x \quad (x = p, d) \tag{1.1}$$

were extracted by following the scheme of Fig. 1, where only the most important and interesting processes are presented. The early methods applied with liquid hydrogen made use of the detection of the γ ray following the $pd\mu$ fusion [3] or the muonic x rays emitted during the deexcitation of the $(\mu\mathrm{Ne})^*$ complex [4]. In the first case, the determination of the transfer rates was relatively indirect, while the use of a NaI detector in the second one made it difficult to get rid of the background contribution (poor energy resolution). This may explain why the results of these experiments were not in agreement with each other. However, it is worthwhile to notice that they discovered a transfer rate $\Lambda_{d\mathrm{Ne}}$ exceeding the value of $\Lambda_{p\mathrm{Ne}}$ by about an order of magnitude. This observation was in strong disagreement with the calculation by Gershtein published one year later [1].

Transfer experiments in gas mixtures were performed at pressures between 6 and 45 bars a few years later [5–7]. The experimental techniques used the time signature of the electrons resulting from muon decay, or the yield dependence of the muonic Xe(2-1) transition on the concentration of a third part element Z in mixtures of $H_2 + Xe + Z$. The results of the gas experiments were found in disagreement between each other and those obtained in liquid (see Ref. [8] for a review).

The measurements reported in this paper aim to clarify the subject of muon transfer from μp and μd in the ground state to neon in binary gas mixtures at pressures from 7 to 40 bars. The method has three important advantages compared to the pioneering experiments.

(1) The muonic neon x rays are directly measured by germanium detectors which have good energy and timing resolutions. This is of great help to reduce and take precisely into account the background contribution.

(2) The entire time range from the times preceding the muon arrival up to several μp (or μd) lifetimes can be analyzed. This permits us to observe very early times (a few tens of nanoseconds) after muon stop in hydrogen where

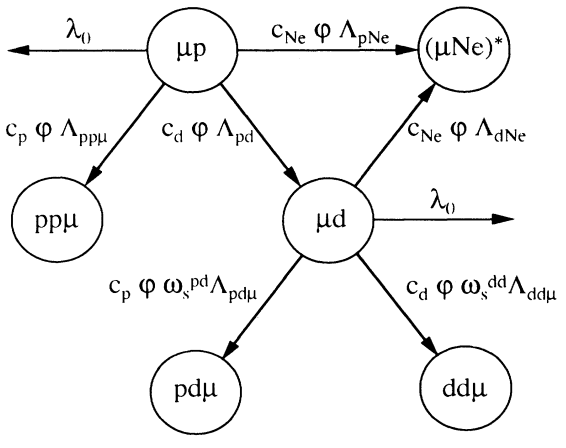

FIG. 1. Scheme of the reactions following the muon stop in a mixture of protium, deuterium, and neon. Only the processes of interest are presented.

epithermal muonic hydrogen or deuterium may still exist and perform transfer reactions. This method should be sensitive to an energy dependence of the transfer rate up to the eV energy region.

(3) The muonic x ray analysis is a powerful method for checking a possible contamination of the gas mixture by impurities. If their presence is revealed, their effect corresponds to additional transfer channels of the muon and this contribution can be accurately determined and subtracted.

Partial results of this experiment have already been reported [9]. Most of them have been confirmed, while others are in contradiction with this paper. This subject will be discussed in detail in Sec. IV.

II. MEASUREMENT

Two vessels have been employed depending on the total pressure: up to 15 bars a stainless steel vessel of about 9 liters described in Ref. [10], and a new silver-plated vessel of about 6 liters designed for 40-bar measurements [11]. All mixtures have been measured at room temperature after being prepared at about 150 bars by an industrial factory (Carbagas, Bern) which certified their homogeneity and the relative concentration of the components within ±1% precision, but ±2% for the H_2+0.7%Ne (following this notation, the concentration corresponds to the ratio of partial neon pressure to the total) mixture.

Two coaxial germanium detectors have been simultaneously used for all measurements except at 15 bars. At the energy of the muonic neon $2p$-$1s$ transition (207 keV), one achieved typical energy and time resolutions [full width at half maximum (FWHM)] of 1.1 keV and 13.0 ns for one detector and 0.90 keV and 9.0 ns for the other. Time bins were 1.0 to 1.8 ns wide depending on the measurement.

X-ray data were recorded event by event on tape and the spectra formed off line for the final evaluation. The efficiency curves of the detectors have been determined with the help of radioactive sources. The attenuation of the x rays passing through the target walls has been taken into account for the normalization of the x-ray intensities. However, this procedure was not suitable for high pressure (40 bars) measurements, because of the particular geometry of the vessel and window assembly. In this case, the efficiency curve has been determined using the $H_2 + 2.0\%$Ne data measured with the same vessel by assuming that the Lyman series intensity pattern is identical to others measured at 15 bars.

The background subtraction in the time spectra has been performed in the same manner as described in Ref. [10].

III. ANALYSIS

A. Transfer rates $\Lambda_{p\mathrm{Ne}}$ and $\Lambda_{d\mathrm{Ne}}$

One usually assumes that the yield at which muonic protium (deuterium) atoms disappear is proportional to the number of these atoms (decay law):

$$\frac{dN_{\mu x}}{dt}(t) = -\lambda_x N_{\mu x}(t) \quad (x = p, d) \; . \tag{3.1}$$

If the rates of all disappearance channels do not depend on the kinetic energy of the muonic hydrogen and deuterium atoms (one, however, knows that this assumption is not totally correct in the cases of $pd\mu$ and $dd\mu$ molecular formations, but the overall contribution of these processes is very small in these experimental conditions), then λ_x is a constant only depending on the mixture characteristics (see Fig. 1). In this case, the time distribution of the muonic x rays emitted by the excited neon atoms after muon transfer has the well-known single exponential structure

$$\begin{aligned}\frac{dN^{\gamma}}{dt}(t) &= -\frac{c_{\mathrm{Ne}}\,\varphi\,\Lambda_{x\mathrm{Ne}}}{\lambda_x}\,\frac{dN_{\mu x}}{dt}(t) \\ &= N^0_{\mu x}\,c_{\mathrm{Ne}}\,\varphi\,\Lambda_{x\mathrm{Ne}}\,e^{-\lambda_x t} \quad (x = p, d) \; ,\end{aligned} \tag{3.2}$$

where φ is the relative atomic density of the mixture with respect to liquid hydrogen at boiling point (4.25×10^{22} atoms/cm^3), c_{Ne} is the neon concentration, and $N^0_{\mu x}$ is the total number of μx-atoms formed at time $t = 0$. The total disappearance rate λ_p for μp, respectively, λ_d for μd-atoms, can then be written as

$$\lambda_p = \lambda_0 + \varphi(c_p\Lambda_{pp\mu} + c_d\Lambda_{pd} + c_{\mathrm{Ne}}\Lambda_{p\mathrm{Ne}}) \; , \tag{3.3}$$

$$\lambda_d = \lambda_0 + \varphi(c_p\omega_s^{pd}\Lambda_{pd\mu} + c_d\omega_s^{dd}\Lambda_{dd\mu} + c_{\mathrm{Ne}}\Lambda_{d\mathrm{Ne}}) \; . \tag{3.4}$$

ω_s^{pd} and ω_s^{dd} are the effective muon sticking coefficients after both fusion reactions, while c_p and c_d are the atomic fractions of each hydrogen isotope ($c_p + c_d + c_{\mathrm{Ne}} = 1$). Only small quantities (typically less than 1%, compared to hydrogen) of neon were used, because of the large values of the transfer rates compared to other channels.

From the total disappearance rate λ_x deduced by fitting the muonic x-ray time spectra, one can then easily determine $\Lambda_{x\mathrm{Ne}}$ using Eqs. (3.3) or (3.4). If hydrogen contains even a noticeable fraction of deuterium, Eq. (3.2) is not sufficient to describe the time structure of the neon x rays and other terms have to be added, regarding Fig. 1. Because one did not use isotopically pure protium, but natural hydrogen (deuterium concentration of about 150 ppm), this effect had to be taken into account.

Only the $2p$-$1s$ time spectra had enough intensity for detailed analysis; these results were then checked by making use of the $3p$-$1s$ or $4p$-$1s$ time spectra. As shown in Fig. 2 for mixtures of H_2+2.0% Ne measured at 15 and 38 bars, the time structure of neon x rays after muon transfer from μp atoms has a single exponential distribution. The time distribution of the neon x rays following the two-step process: $\mu p + d \rightarrow \mu d + p$, $\mu d + \mathrm{Ne} \rightarrow \mu\mathrm{Ne} + d$, has been taken into account during the analysis. However, its contribution (which can be analytically described as the difference of two exponential functions) to the overall scheme is very small. Using Eq. (3.3), the transfer rate $\Lambda_{p\mathrm{Ne}}$ can be determined. However, a careful analysis of the delayed energy spectra revealed the characteristic transitions from the muonic Lyman series of carbon and/or oxygen in two of the mixtures. These exhibited decay rates similar to those of neon x rays, and

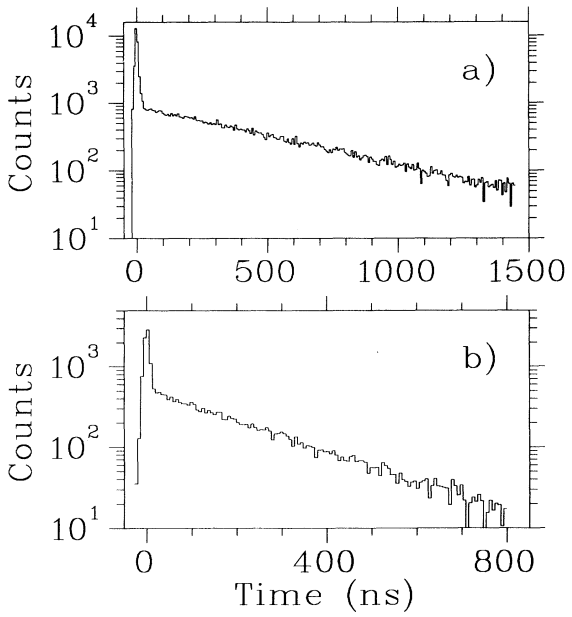

FIG. 2. Net time spectra of the muonic Ne(2-1) transition after muon transfer from muonic protium measured in mixtures of $H_2 + 2.0\%$Ne. The sharp peak is due to direct muon capture in neon and muon transfer from excited μp^*. These measurements have been performed at (a) 15 bars and (b) 38 bars (6.5 ns/bin for both spectra).

their intensity patterns were typical of muon transfer [12]. Therefore one can state that these impurities were mixed in the gas. By performing a detailed analysis of the carbon and oxygen lines based on the reasonable assumption that the Lyman series intensity for each element Z is proportional to $c_Z \Lambda_{pZ}$, the concentrations of about 30 ppm CO_2 in one case (from a previous measurement performed with an $Ar + CO_2$ mixture) and 60 ppm O_2 (H_2O or O_2) in the second were deduced. The pseudotransfer rate $\Lambda_{p\mathrm{Ne}}$ given in the third row of Table I has then to be corrected to take into account these additional transfer channels.

The corrected transfer rates to neon determined for each mixture are found in good agreement with each other, the average value being

$$\Lambda_{p\mathrm{Ne}} = (0.0849 \pm 0.0018) \times 10^{11}\ \mathrm{s}^{-1} .$$

TABLE I. Reduced transfer rates from muonic protium to neon at room temperature. The "uncorrected"-labeled values are those obtained without applying the impurity yield correction (see text for details).

Mixture	Pressure (bar)	$\Lambda_{p\mathrm{Ne}}$ uncorrected (10^{11} s^{-1})	$\Lambda_{p\mathrm{Ne}}$ corrected (10^{11} s^{-1})
$H_2 + 0.7\%$Ne	15	0.0886(34)	0.0777(56)
$H_2 + 1.4\%$Ne	15	0.0848(26)	0.0803(33)
$H_2 + 2.0\%$Ne	15	0.0858(20)	0.0858(20)[a]
$H_2 + 2.0\%$Ne[b]	38	0.0877(26)	0.0877(26)[a]
Mean value			0.0849(18)

[a]No impurity correction had to be applied for this mixture.
[b]Average value of both detectors.

Two Ne(2-1) time spectra measured in $D_2 + $Ne mixtures are presented in Fig. 3. Their deviation from a single exponential distribution is clear. The shape of these time spectra presents some similarities with those of oxygen in $H_2 + SO_2$ mixtures [13,14]. In the present case, the time structure has a hunchbacked shape up to about 100 or 300 ns depending on the experimental conditions (time zero is defined as the direct capture peak centroid) and an exponential behavior only later. This suggests that, unlike the muon transfer to neon from μp atoms, the transfer rate from μd atoms to neon depends on the kinetic energy of the muonic deuterium atom.

The evaluation procedure was divided into two parts: determination of the transfer rate $\Lambda^{\mathrm{th}}_{d\mathrm{Ne}}$ corresponding to thermalized μd atoms, by fitting only the exponential part of time spectra, then guessing an energy dependence of $\Lambda_{d\mathrm{Ne}}(E)$ explaining the shape of the time spectra.

The first part was completed the same way as for $H_2 +$ Ne spectra. The presence of impurities was revealed with quite high concentrations (90 ppm O_2 and 40 ppm N_2) in $D_2 + 0.43\%$Ne, and (70 ppm O_2 and 10 ppm N_2) in $D_2 + 0.40\%$Ne mixture, but the $D_2 + 0.20\%$Ne mixture contained only 10 ppm N_2. The presence of about 0.3% H_2 in the deuterium had a negligible effect. As shown by Table II, the impurity corrections amount from 1.5% to 6% for the value of $\Lambda^{\mathrm{th}}_{d\mathrm{Ne}}$, with an averaged value on all measurements of

$$\Lambda^{\mathrm{th}}_{d\mathrm{Ne}} = (1.010 \pm 0.026) \times 10^{11}\ \mathrm{s}^{-1} .$$

The search for an energy dependence of the transfer

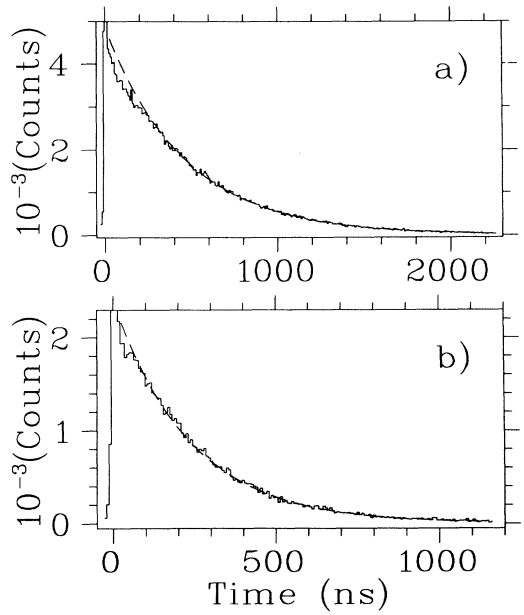

FIG. 3. Net time spectra of the muonic Ne(2-1) transition after muon transfer from muonic deuterium measured in mixtures of (a) $D_2 + 0.40\%$Ne at 7 bars (9 ns/bin) and (b) $D_2 + 0.43\%$Ne at 15 bars (8 ns/bin). The sharp peak is due to direct muon capture in neon and muon transfer from excited μd^*. The dashed line corresponds to a purely exponential distribution.

TABLE II. Reduced transfer rates from muonic deuterium to neon at room temperature. These values have been obtained by fitting only the exponential region of the time spectra. The "uncorrected"-labeled values are those obtained without applying the impurity yield correction (see text for details).

Mixture	Pressure (bar)	Λ_{dNe}^{th} uncorrected (10^{11} s^{-1})	Λ_{dNe}^{th} corrected (10^{11} s^{-1})
$D_2 + 0.40\%Ne$[a]	7	1.038(22)	1.010(26)
$D_2 + 0.43\%Ne$	15	1.017(17)	0.959(32)
$D_2 + 0.20\%Ne$[a]	39	1.071(29)	1.055(30)
Mean value			1.010(26)

[a]Average value of both detectors.

rate $\Lambda_{dNe}(E)$ which could produce time spectra matching with the experimental data was made difficult because of the lack of theoretical calculations about this reaction. One also had to infer empirical and simple energy dependences with a reduced set of free parameters.

Because the Ne(2-1) data from the $D_2 + 0.40\%Ne$ at 7 bars measurement presented the largest deviation from the exponential distribution and had by far the highest statistics, it was naturally chosen for monitoring the search procedure, which was performed on a time range from 25 to 2250 ns after muon stop in the gas to avoid any contribution from the direct capture peak in neon.

The initial energy distribution of the μd atoms at the end of the cascade was taken from Markushin [15]. He demonstrated that, at pressures around 10 bars, about 40% of the muonic hydrogen atoms are created with a high energetic component from 10 eV extending up to 200 eV, which is due to the Coulomb deexcitation during the atomic cascade. The program TRANSFER, written by Adamczak [16], is a Monte Carlo simulation program which calculates the reactions between $(\mu p)_{1s}$, respectively, $(\mu d)_{1s}$, atoms in mixtures of hydrogen, respectively, deuterium, containing small amounts of higher Z substances. The energy-dependent scattering cross sections are taken from Ref. [17]. The transitions between the hyperfine states of the muonic hydrogen atoms are taken into account during the thermalization procedure. The transfer rates of reactions (1.1), and their energy dependence have to be given directly inside the code source in the form of parametrized analytical functions. The program output contains the time spectrum of the muonic x rays emitted after muon transfer, the deexcitation of the $(\mu Z)^*$ atom being considered as instantaneous.

The choice between different empirical $\Lambda_{dNe}(E)$ dependences was achieved using a χ^2-minimization method to compare the experimental and simulation histograms. Two time regions and corresponding normalized χ^2 values (χ_1^2, χ_2^2) were defined. The first region covered the time range from 25 ns to 425 ns, where the shape of the Ne(2-1) time spectrum deviates strongly from an exponential distribution, and the second one the interval from 426 ns to 2250 ns. A constant value of the muon transfer rate from muonic deuterium to neon $\Lambda_{dNe} = \Lambda_{dNe}^{th}$ (uncorrected value) yielded values of $\chi_1^2 = 1.93$ and $\chi_2^2 = 1.03$. A much better agreement ($\chi_1^2 = 1.11$ and $\chi_2^2 = 1.02$) between experiment and calculation was reached by guessing the empirical dependence:

$$\Lambda_{dNe}(E) = \Lambda_{dNe}^{th} \times \begin{cases} 1.0, & 0 < E < E_1 \\ 0.8, & E_1 \le E < E_2 \\ 1.1, & E \ge E_2 \end{cases} \quad (3.5)$$

with $E_1 = 0.07$ eV and $E_2 = 0.5$ eV. Eventually it appeared that the fit was only slightly sensitive to the value of E_2 in the range from 0.5 to 1.0 eV. The corresponding enhancing factor of 10% from Λ_{dNe}^{th} led to the best χ^2 value, but setting this value to one led to only tiny worse χ^2 values of 1.18 and 1.02 for each time region. Therefore the value $E_2 = 0.5$ eV is a lower limit, according to the time resolution of the detection system. We estimate the uncertainty on the energy E_1 and on the constants 0.8 and 1.1 contained in formula (3.5) to be within 10%. Of course the squared distribution described by the formula is only a crude estimate of what the real function should look like. It is therefore not reasonable to ask for more precise values for its related parameters and their uncertainty from these experimental data. However, it is essential to observe that this function agrees with the other time histograms of the neon Lyman series and for both detectors in $D_2 + 0.40\%Ne$ at 7 bars. In addition, when applied to the experimental conditions of the two other mixtures, it satisfactorily reproduces the experimental time spectra. This proves that the behavior of the neon x-ray time spectra can be simply explained by the energy dependence of the muon transfer rate from μd to neon.

B. Intensity patterns

When using the 15-bar vessel, the efficiency calibration of the x-ray detectors was made off line, with radioactive sources of ^{133}Ba, ^{152}Eu, and ^{182}Ta which widely cover the energy range of interest.

The delayed Lyman series of neon for a mixture of $H_2 + 2.0\%Ne$ is presented in Fig. 4(a). Only the Lyman series transitions from 2-1 to 6-1 are observed. In comparison, the (prompt) Lyman series resulting from direct muon capture in neon would exhibit many higher $(n-1)$ transitions. The intensity patterns of all the H_2+Ne mixtures measured at 15 bars are shown in Table III. They agree very well with each other and only slightly differ from the intensity pattern deduced from the prediction of Holzwarth and Pfeiffer [18] with the initial level of transfer in neon set to $n_p = 6$, and using the cascade code of Akylas and Vogel [19]. The cascade calculations were performed by assuming that the neon atom is neutral at transfer time. The value of the electronic K-shell refilling width had a negligible effect on the resulting intensity pattern.

Figure 4(b) shows the delayed Lyman series of neon after muon transfer from muonic deuterium. By comparing with Fig. 4(a), one remarks the appearance of the Ne(7-1) line, indicating that the transfer occurs (at least partially) in this case to the level $n_d = 7$. The neon intensity pattern in the $D_2 + 0.20\%Ne$ mixture has been

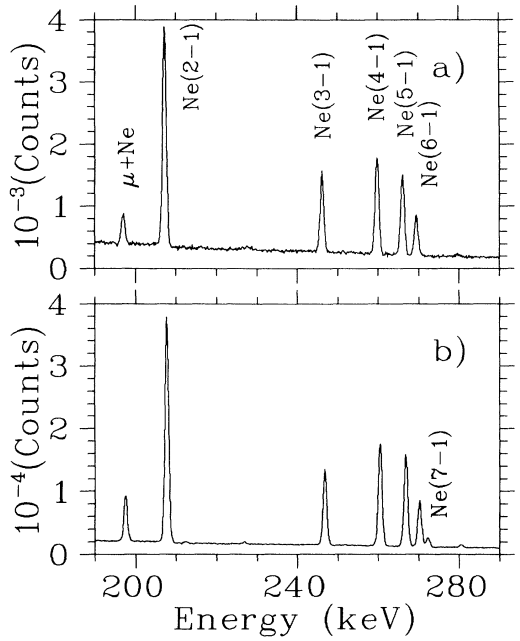

FIG. 4. Delayed energy spectra of the muonic Lyman series of neon produced after muon transfer from (a) μp (H_2 + 2.0%Ne at 15 bars) and (b) μd (D_2 + 0.40%Ne at 7 bars). The time cuts are set in case (a) from 40 to 1500 ns, and in case (b) from 30 to 4600 ns after time zero, which is given by the direct capture peak centroid. One notices the presence of the μNe(7-1) line by muon transfer from muonic deuterium.

determined from the H_2 + 2.0%Ne data obtained with the same vessel and at comparable pressure.

Table IV shows that the intensity pattern due to muon transfer to neon does not depend on neon concentration, or on the pressure of the mixture, as already mentioned in the case of muon transfer to argon [10]. Setting different delayed time cuts did not modify them either. This indicates clearly that only the transfer from the ground state of μp and μd atoms is observed on the whole delayed time range, and that the muon transfer to neon proceeds always to the same level and with the same associated angular momentum distribution independently of its kinetic energy.

IV. DISCUSSION

A. Transfer rates $\Lambda_{p\mathrm{Ne}}$ and $\Lambda_{d\mathrm{Ne}}$

Early experimental results obtained at 15 bars with a mixture of H_2 + 0.7%Ne have been reported in 1990 [9]. A very surprising time structure exhibiting two decay components of the muonic neon x rays was observed at that time. The electronics setting was exactly the same as the one used for an experiment using a mixture of H_2+Ne+Ar, which directly followed. Since then, these x-ray data have been carefully reanalyzed and yielded results similar to those published in Ref. [9]. No mistake has been found in the data evaluation.

A second measurement with the same neon concentration (also presented in this paper) performed a year after the first one, provides results in contradiction with the former. These new data show that the delayed part of the muonic neon x-ray time spectra exhibits only one exponential component. The transfer rate to neon deduced from the slope is 25% higher than before. On the other hand, the delayed intensity patterns of the muonic Lyman series of neon of both measurements are identical. However, one has to conclude that due to a nonidentified cause (probably related to the time signal processing) the measurement of the first H_2 + 0.7%Ne mixture has gone wrong.

Reference [9] also reported on another method for determining the transfer rate to neon using the intensities of the delayed Lyman series of neon and argon, and assuming that they are proportional to the transfer rates to each element. The intensities of the whole Lyman series were obtained by scaling the $2p$-$1s$ intensities by the same factor (0.40), according to the knowledge at that time. Very recent (not all published yet) measurements of muon transfer from μp or μd to neon and argon indicate that this approximation was not correct. While the intensity ratios $I_{2-1}/\Sigma I_{n-1}$ after muon transfer from hydrogen and deuterium to argon are almost equal (0.42 and 0.41), it is 0.39 from muonic hydrogen, and 0.35 from muonic deuterium to neon. The determination of A_t(Ne, Ar), the per-atom capture ratio by transfer is therefore more delicate than previously assumed. In addition, the estimates (based on predictions and experimental results from other groups) for the transfer rate from muonic deuterium to neon and argon were later not confirmed by the experiment. These changes have an important influence

TABLE III. Intensity pattern of the muonic Lyman series of neon after muon transfer from protium at 15 bars. The last column gives the pattern obtained with the model of Holzwarth and Pfeiffer, and taking $n_p = 6$.

Transition	Neon concentration			Average	Ref. [18]
	0.7%	1.4%	2.0%	value	
Ne(2-1)	0.3865(93)	0.3932(102)	0.3865(92)	0.3886(55)	0.3524
Ne(3-1)	0.1510(38)	0.1480(37)	0.1476(36)	0.1488(22)	0.1541
Ne(4-1)	0.2072(51)	0.2040(51)	0.2058(49)	0.2057(29)	0.2235
Ne(5-1)	0.1688(42)	0.1663(43)	0.1718(41)	0.1691(25)	0.1890
Ne(6-1)	0.0865(24)	0.0885(25)	0.0883(23)	0.0878(14)	0.0810

TABLE IV. Intensity pattern of the muonic Lyman series of neon after muon transfer from deuterium. The last column gives the pattern obtained with the model of Holzwarth and Pfeiffer ($n_d = 7$).

Transition	Neon concentration			Average value	Ref. [18]
	0.40% (7 bars)[a]	0.43% (15 bars)	0.20% (39 bars)[a]		
Ne(2-1)	0.3545(57)	0.3544(89)	0.3483(69)	0.3526(40)	0.3439
Ne(3-1)	0.1390(23)	0.1411(33)	0.1442(31)	0.1409(17)	0.1479
Ne(4-1)	0.2051(33)	0.2046(48)	0.2088(43)	0.2060(23)	0.2133
Ne(5-1)	0.1859(30)	0.1852(44)	0.1842(39)	0.1853(21)	0.1832
Ne(6-1)	0.0959(16)	0.0956(23)	0.0956(23)	0.0958(12)	0.0850
Ne(7-1)	0.0196(4)	0.0191(6)	0.0189(10)	0.0194(4)	0.0267

[a]Average value of both detectors.

on the determination of $\Lambda_{p\mathrm{Ne}}$, too.

If we make use of the updated values about the muon transfer from μp and μd to argon and neon, we obtain a higher value for $\Lambda_{p\mathrm{Ne}}$ which is in agreement with that reported in this paper. Hence all measurements of the transfer rate $\Lambda_{p\mathrm{Ne}}$, but one, give the same value. This statement confirms the opinion stressed in the above paragraph that the transfer rate $\Lambda_{p\mathrm{Ne}}$ deduced from the first measurement of the H_2 + 0.7%Ne mixture has to be corrected according to the new data presented in this paper.

The deviation from a purely exponential structure observed on neon time spectra after muon transfer from μd is important (see Fig. 3). Because of the non-negligible contamination of the gas mixture D_2 + 0.43%Ne by oxygen and nitrogen impurities, one could argue that this deviation may only be due to the influence of transfer to these contaminants, instead of an irregularity in neon transfer. Moreover, the transfer to oxygen is well known for its very singular behavior [13,14] in gas mixtures of $H_2 + SO_2$. There are three strong arguments which contradict this hypothesis. First of all, it does not agree with what is observed in H_2 + 0.7%Ne, which was found contaminated by CO_2, and where the shape of the neon x-ray time spectra was exponential in very good approximation (i.e., in the limit of the experimental statistics), while carbon and oxygen x rays are known for exhibiting "convex"-shaped time spectra. The second reason is based on Monte Carlo simulations performed with a mixture of D_2+0.43%Ne+0.0090%O_2+0.0040%N_2, assuming a constant rate for $\Lambda_{d\mathrm{Ne}}$. These show that the neon x-ray time spectrum is exponential at comparable statistics with measurement. Finally, one can simply argue that the time spectrum of neon in D_2 + 0.20%Ne measured at 40 bars has a similar shape as the one measured at 15 bars in spite of a much smaller nitrogen contamination.

The reason for the large difference between $\Lambda_{p\mathrm{Ne}}$ and $\Lambda^{\mathrm{th}}_{d\mathrm{Ne}}$ has been qualitatively explained by Sayasov [20], who suggested that the transfer probability contains an oscillating factor which has to be taken into account in the muon transfer process. According to this explanation, the transfer probability has exactly a minimum in the case of muon transfer from muonic hydrogen to neon (see Fig. 3 from Ref. [21]).

B. Intensity patterns

The measurements performed with H_2 + Ne mixtures show that the intensity patterns of the muonic Lyman series of neon stay constant by increasing the neon concentration by a factor of 3 (see Table III). On the other hand, one can observe that they do not vary between 7 and 40 bars for D_2 + Ne mixtures (see Table IV). This is confirmed by similar measurements performed with H_2 + Ar gas mixtures on a wider pressure range from 10 up to 150 bars [10].

From simple energy-based arguments (reduced mass difference) one would expect that the muonic level of transfer would be less from muonic deuterium compared to muonic protium, i.e., $n_d \leq n_p$. The present experimental data of muon transfer to neon atoms indicate the opposite. This tendency has already been observed in the case of muon transfer to oxygen [14].

The calculations by Holzwarth and Pfeiffer [18], which *ab initio* only intended the investigation of the transfer reaction $\mu p + \mathrm{F} \rightarrow \mu\mathrm{F} + p$, can be used to predict the initial level n where the muon transfer should occur in low Z from muonic protium and deuterium, and the associated angular momentum distribution. In the case of neon, these calculations give $n_p = 8$ for protium and $n_d = 7$ for deuterium. Although prediction and experiment agree for μd, the calculation fails for μp. If one adjusts the value $n_p = 6$ to make it match with the experimental observation, one remarks that the experimental and theoretical intensity patterns for muon transfer from both hydrogen isotopes to neon are in fair agreement with each other (see Tables III and IV).

Making use of the code by Akylas and Vogel [19], one can also deduce the muon population of the p subshell at the level of transfer. For muon transfer from μp, one gets $P_{\mu p}(n = 6, l = 1) = 0.387 \pm 0.007$, which compares fairly well with the theoretical value of 0.357. Applying the same method in the case of muon transfer from μd, the result is $P_{\mu d}(n = 7, l = 1) = 0.234 \pm 0.005$, but 0.321 from Ref. [18]. Obviously, these values differ strongly. If one believes that the theoretical angular momentum distributions are right, the disagreement drops by assuming that the muons may not only transfer to the level $n_d = 7$, but are distributed between levels $n_p = 6$ and 7 with a

probability of about 3/4 to the higher level. Because the Lyman series intensity structure does not depend on the choice of the delayed time cut, this ratio should be independent of the kinetic energy of the muonic deuterium atom.

V. CONCLUSION

The transfer rate $\Lambda_{p\mathrm{Ne}}$ is found to be non-energy-dependent in the range from thermal energies (room temperature) up to about 0.5 eV, considering the time resolution of the experimental setup (essentially depending on the muon slow down in the gas mixture and the x-ray signal processing by the electronics). This limit has been estimated by making use of transfer process Monte Carlo (MC) simulations. The muon transfer rate from deuterium to neon is more than one order of magnitude higher than $\Lambda_{p\mathrm{Ne}}$ at thermal energies and also exhibits some energy dependence at higher energies, i.e., beyond $\sim$0.07 eV. Gershtein [1] predicted that for $E_{\mu d} \gg 0.02$ eV, the transfer rate should have a $\Lambda_{d\mathrm{Ne}} \propto E_{\mu d}^{-1}$ dependence. The experimental data presented in this paper tend towards a much higher limit for this approximation, which cannot be less than 1 eV. Studying a higher energy region would require lower pressure measurements with better time resolution. Another method can make use of triple gas mixtures such as H_2+D_2+Ne, where c_d should not exceed about 5%. Very fast μd atoms are formed in this case by transfer from μp. These are then mainly slowed by scattering on hydrogen molecules down to 1–2 eV where the scattering cross section $\sigma_{\mu d+p}$ is very small, because of the Ramsauer-Townsend effect. The study of neon is even ideal, because $\Lambda_{p\mathrm{Ne}} \ll \Lambda_{d\mathrm{Ne}}$, such that the contribution of the channel $\mu p \rightarrow \mu d_{(1\mathrm{eV})} \rightarrow \mu\mathrm{Ne}$ is much higher than the others, i.e., $\mu p \rightarrow \mu\mathrm{Ne}$ and $\mu d \rightarrow \mu\mathrm{Ne}$. New experiments based on this method are under way. On the other hand, a different theoretical approach for calculating the transfer rates to bare nuclei is being developed [22]. This makes use of the multichannel adiabatic approximation and has already been successfully applied for muon transfer between hydrogen isotopes.

We have shown that the behavior of the neon x-ray time spectra due to muon transfer from muonic deuterium can be understood assuming that the transfer rate of this process is energy dependent. This result suggests that the muon transfer reaction to other elements, such as carbon, fluorine, or oxygen [14], can be explained in the same manner. A study of muon transfer from muonic protium and deuterium to oxygen is actually in progress, which is based on this hypothesis.

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