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MEASUREMENT OF THE RATE OF TRANSFER OF A MUON FROM A $p\mu$ ATOM TO NUCLEI OF OTHER ELEMENTS

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The rate of transfer of a negative muon from a $p\mu$ atom to the nuclei of carbon, argon, and xenon has been measured with a gas target filled with hydrogen to a pressure of 45 atm, and scintillation counters. The transfer rates obtained (referred to the density of normal liquid hydrogen), $\lambda_C = (5.1 \pm 1.0) \times 10^{10}$ sec^{-1}, $\lambda_{Ar} = (12.0 \pm 1.9) \times 10^{10}$ sec^{-1}, and $\lambda_{Xe} = (44.6 \pm 3.6) \times 10^{10}$ sec^{-1}, are in good agreement with the dependence $\lambda_Z \sim Z$.

THE process of transfer of a negative muon from a K orbit of a $p\mu$ atom to nuclei of elements with $Z > 2$

$$p\mu + Z \rightarrow Z\mu + p \qquad (1)$$

has been observed upon stopping of muons both in gaseous hydrogen (diffusion chamber)[1-3] and in liquid hydrogen (bubble chamber)[4]. Here the concentrations of atoms of other elements were small, amounting to 0.1—0.01%. The following characteristic features of this process have been established. Work at our laboratory [1,2] has shown that the transfer of the muon proceeds preferentially to high orbits of the mesic atoms of carbon and oxygen with a principal quantum number $n \approx Z$. This is indicated by observation of slow Auger electrons (with an energy of several keV) arising in the cascade transition of the muon from the high orbits of the $Z\mu$ atom to the ground state. From the fact that recoil protons are not observed in reaction (1), the conclusion has been drawn [2] that the probability of transfer of a muon from a $p\mu$ atom directly to the ground state of $C\mu$ and $O\mu$ atoms is less than 3%.

The absolute transfer rate has also been determined [1-3] to C and O nuclei, and in the work of Conforto et al.,[5] with inclusion of Schiff's data,[4] the transfer rate to neon. The absolute transition rate of the muon to all the nuclei studied (C, O, Ne), defined as the transition rate for a concentration of atoms with $Z > 1$ in liquid hydrogen $C_Z = 1$, amounts to $\lambda_Z = (2-3) \times 10^{10}$ sec^{-1}. It must be noted that the significant feature of these investigations was the determination of the relative transition rates $\lambda_Z C_Z$; because of the difficulty of determining the absolute concentration C_Z of atoms of other elements in the chambers, λ_Z was determined with a large uncertainty.

All of the experimental results enumerated above have been satisfactorily explained by Gershteĭn,[6] who showed that the mechanism of muon transfer to nuclei of other elements is related to the existence of molecular term crossing in the $p\mu Z$ system.

The purpose of the present work was to measure the absolute transfer rate as a function of nuclear charge Z for a wide range of Z. We have measured the transfer rates to nuclei of carbon, argon, and xenon. The main process by which the muon disappears after formation of a $p\mu$ atom in pure hydrogen is the decay $\mu^- \rightarrow e^- + \nu + \nu$ with a rate 0.45×10^6 sec^{-1}. For mesic atoms with rather large Z, such as argon and xenon, the nuclear capture rate of the muons considerably exceeds the decay rate. The method used in the present work to measure the rate of the transition (1) is based on measurement of the counting rate of decay electrons as a function of the concentration of atoms with $Z > 1$ in gaseous hydrogen. Direct measurement by this method of the transfer rate to carbon is hindered by the fact that the nuclear capture rate in carbon is small and amounts only to about 10% of the decay rate. Therefore for carbon we used the following method of measurement. Pure hydrogen was diluted in advance with atoms of argon or xenon to the concentration at which the counting rate of electrons approached a minimum value. Under these conditions the addition of carbon atoms leads to a competition between transitions to carbon and argon or xenon, as the result of which the electron counting rate is restored with increasing concentration of carbon atoms.

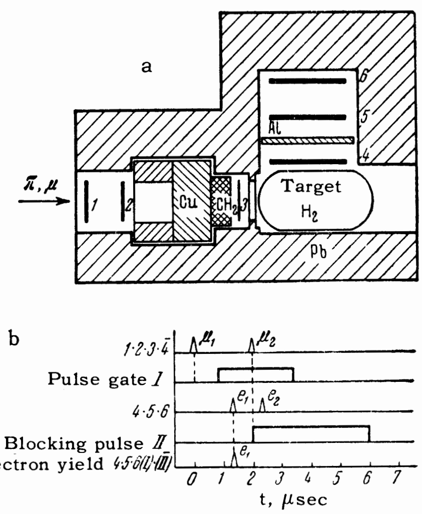

FIG. 1. Drawing of experimental apparatus (a) and time scale of the pulses (b).

A diagram of the experimental arrangement is shown in Fig. 1. The time scale of operation of the electronics is also shown in this figure. A 260-MeV/c beam of π^- and μ^- mesons is monitored by a telescope of three scintillation counters 1—3. The dimensions of each scintillator are $10 \times 10 \times 0.5$ cm. Absorption of π mesons and slowing down of muons is achieved by an absorber consisting of layers of 95 g/cm^2 CH_2. The muons stop in the gas target, which is filled with hydrogen to a pressure of 45 atm. The target is a stainless steel vessel 25 cm long, 16 cm in diameter and with a 3-mm wall thickness. A telescope of three scintillation counters 4—6 serves to detect decay electrons. The dimensions of counter 4 are $15 \times 20 \times 1$ cm, and the dimensions of counters 5 and 6 are $20 \times 20 \times 1$ cm. The monitor telescope uses type FÉU-36 photomultipliers, and the electron detection telescope—type AVP-56 photomultipliers. The following measures were taken to reduce the background.

1. The optimum times were chosen for the delay of the muon pulse, which amounted to $\tau_d = 0.89$ μsec in the experiments, and the gate width, which was $\tau_g = 2.62$ μsec. The times τ_d and τ_g were calibrated with an accuracy of 4% and were checked in a control experiment in which the lifetime of muons in carbon was measured with the same apparatus. The measured lifetime $\tau_C = 2.07 \pm 0.09$ μsec is in good agreement with the accurate value $\tau_C = 2.043 \pm 0.003$ μsec.[7]

2. Anticoincidences were employed between the pulses of counter 4 and the pulse of the monitor telescope 1—3 in the time interval 0—100 nsec.

3. The electron detection channel was blocked on appearance in the time interval $\tau_d + \tau_g$ of a second pulse in the monitor telescope.

4. Coincidence circuits were used with a resolving time of 3 nsec,[8] whose sensitivity was increased to 0.2 V by double shaping of the input pulses by tunnel diodes.

5. An additional aluminum absorber 1.5 cm thick was used, which was located between counters 4 and 5, and which removed the background of low energy charged particles.

6. The apparatus was shielded by a circular layer of lead at least 20 cm thick; light materials, including air, were removed from the region near the target.

Background measurements, which were frequently alternated with measurements of the effect, were made with a vessel evacuated to 10^{-2} mm Hg which was an exact copy of the working target. The ratio of the electron counting rate with the empty target to the counting rate with the target filled with pure hydrogen to 45 atm was 35%. The electron counting rate was 10 counts/min in the monitor telescope.

The target was filled with hydrogen previously purified from other gas impurities to a concentration of 10^{-4} at.%. The concentration of deuterium was 0.7×10^{-2} at.%.[1,2] The gases listed in the table were used as additions to the pure hydrogen. Addition of the gas being studied to the target was carried out from an additional region maintained at a pressure 5—10 atm above that in the target. The concentration of the atoms of the various elements in the hydrogen of the target was determined from the known ratio of the target volume and the additional volume and from the

Element	Gas used	Z	Assumed value of $\lambda_{capt} + \lambda_0$, 10^6 sec^{-1}	λ_Z, 10^{10} sec^{-1}			$\sigma_{p\mu Z}$, 10^{-17} cm^2
				$N_Z = N_p = 2.4 \cdot 10^{21}$ cm^{-3}	$N_Z = N_p = 3.5 \cdot 10^{22}$ cm^{-3}	$N_Z = N_p = 4.25 \cdot 10^{22}$ cm^{-3}	
C	Methane, CH_4 Ethane, C_2H_6	6	0.489	0.28±0.05	4.2±0.7	5.1±1.0	0.54±1.0
Ar	Chemically pure argon	18	2,32	0.68±0.11	9.9±1.5	12.0±1.9	1.3±0.2
Xe	Chemically pure xenon	54	12,1	2.52±0.21	36.8±3.1	44.6±3.6	4.75±0.38

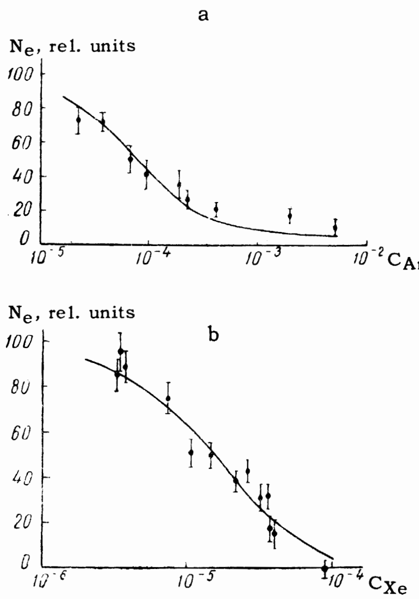

FIG. 2. Dependence of electron counting rate N_e on the concentration of atoms a – of argon, and b – of xenon, in hydrogen.

known pressure difference in these two volumes. For the best mixing and the most accurate determination of the concentrations, the gas being studied was first diluted with hydrogen in the ratio $C_Z/C_H = 1$–10% and was kept in special flasks for several days. The average accuracy of determining the concentrations C_Z in the target volume, which was determined as the ratio of the number of atoms of element Z to the number of atoms of hydrogen, was 5%.

The measured electron counting rates N_e (the ratio of the number of pulses recorded by the counter telescope 4–6 to the number of counts in the monitor telescope) are shown in Figs. 2–4 as a function of the concentrations C_Z. The combined results of several runs are plotted for each of these curves. To determine the rate of transfer of the muon from a pμ atom to the nuclei, we simultaneously analyzed all of the experimental curves given in Figs. 2–4.

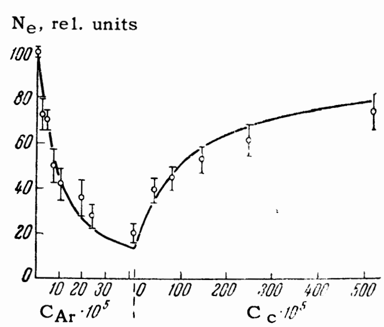

FIG. 3. Dependence of electron counting rate on the concentration of atoms of argon and, for a concentration of argon $C_{Ar} = 4.2 \times 10^{-4}$, on the concentration of carbon atoms.

An analytic expression for the electron counting rate N_e as a function of the concentrations C_Z for the case when atoms of several elements are present in the hydrogen can be found by solving the system of differential equations describing the time dependence of the processes of decay (rate λ_0), mesic molecule formation (rate $\lambda_{pp\mu}$), transfer to a nucleus with charge Z (rate λ_Z), and nuclear capture of the muon (rate λ_{capt}). The solution of this system for n elements with $Z > 1$, integrated over a time interval equal to the gate width, has the form

$$N_e \sim \left[K + \frac{\lambda_{pp\mu}}{\lambda_0 - \alpha}(k - a) + \sum_{i=1}^{n} \frac{(\lambda_z C_z)_i}{\beta_i - \alpha}(k - b_i) \right], \quad (2)$$

where

$$k = \alpha^{-1}[\exp(-\alpha\tau_1) - \exp(-\alpha\tau_2)], \quad \alpha = \lambda_0 + \lambda_{pp\mu}$$

$$+ \sum_{i=1}^{n} (\lambda_z)_i, \quad a = \lambda_0^{-1}[\exp(-\lambda_0\tau_1) - \exp(-\lambda_0\tau_2)],$$

$$b_i = \beta_i^{-1}[\exp(-\beta_i\tau_1) - \exp(-\beta_i\tau_2)],$$

$$\beta_i = (\lambda_0 + \lambda_{capt})_i, \quad \tau_1 = \tau_d, \quad \tau_2 = \tau_d + \tau_g.$$

The combined values used in the analysis for the rates of nuclear capture and decay are shown in the table for each of the elements studied. The data on the nuclear capture rate in carbon

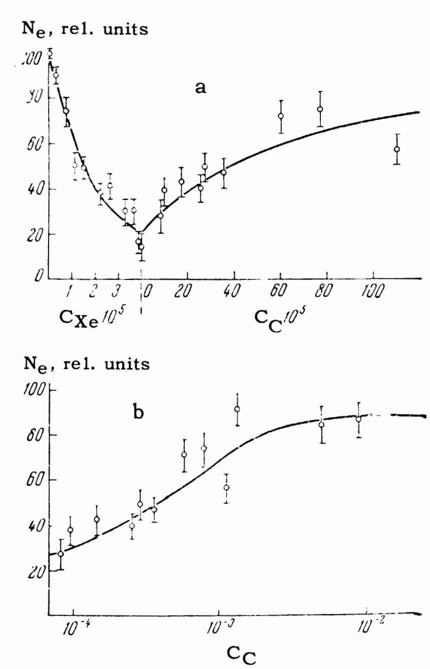

FIG. 4. Dependence of electron counting rate on the concentration of xenon atoms and, for a xenon concentration $C_{Xe} = 4.03 \times 10^{-5}$, on the concentration of carbon atoms (a – small concentrations, b – large concentrations).

$\lambda_{capt}(C)$ were taken from Eckhause et al.[7] Values of $\lambda_{capt}(Ar)$ and $\lambda_{capt}(Xe)$ were found by interpolation of measurements for nuclei with nearby Z.[9] For the rate of formation of the mesic molecule we assumed the value $\lambda_{pp\mu} = 0.11 \times 10^6\ sec^{-1}$ determined on the basis of data for liquid hydrogen by scaling in density.[5,10,11] The combined analysis of all of the experimental dependences according to Eq. (2) was carried out by the method of least squares. We obtained a χ^2 value $\chi^2_{min} = 51$, compared to an expected value $\chi^2 = 42$.

The values found for the parameters λ_C, λ_{Ar}, and λ_{Xe} for the conditions of the present experiment (hydrogen pressure 44.2 atm) are listed in the table. Also given in this table for comparison with other data are the transfer rates for the density of hydrogen in a liquid hydrogen chamber ($N_Z = N_p = 3.5 \times 10^{22}$ atoms/cm^3) and for the density of normal liquid hydrogen ($N_Z = N_p = 4.25 \times 10^{22}$ atoms/cm^3). The final results include corrections ($\leq 10\%$) taking into account formation of $d\mu$ atoms [1] and the difference in transition rate to the nuclei from $p\mu$ and $d\mu$ atoms.[12] The last column of the table lists cross section values for the transition $\sigma_{p\mu Z}$, determined by the expression

$$\lambda_Z = N_Z \sigma_{p\mu Z} v_{p\mu}, \quad (3)$$

where $v_{p\mu}$ is the relative velocity of the $p\mu$ atom, which under our experimental conditions is equal to the velocity of thermal motion, 2.2×10^5 cm/sec.

Comparison with the data of other authors who determined the transition rates to light nuclei shows that the values obtained by these authors, $\lambda_{C,O} = (2.2 \pm 0.9) \times 10^{10}\ sec^{-1}$,[2] $\lambda_{C,O} = (2.6 \pm 1.2) \times 10^{10}\ sec^{-1}$,[3] and $\lambda_{Ne} = (2.78 \pm 0.88) \times 10^{10}\ sec^{-1}$,[5] (reduced to a hydrogen density of $3.5 \times 10^{22}\ cm^{-3}$) agree with the value found in the present work: $\lambda_C = (4.2 \pm 0.7) \times 10^{10}\ sec^{-1}$. However, the average value for the rate of transfer of a muon to light nuclei obtained in the early investigations is somewhat too low. As we have noted earlier, the cause of this apparently is the fact that the concentrations of the admixtures in the works cited [1-4] were actually somewhat smaller than was assumed.

In this connection we can state that the effect of the admixtures with $Z > 1$ in experiments investigating a whole series of mesic atom processes, carried out with a diffusion chamber,[10] were taken into account quite correctly. For example, for the interesting process of scattering of mesic atoms by protons, the cross section for

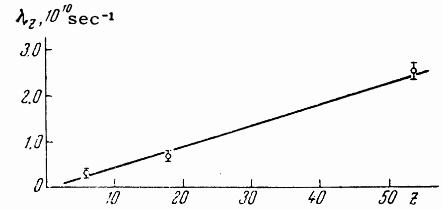

FIG. 5. Dependence of the transfer rate $p\mu + Z \to Z\mu + p$ on nuclear charge Z in hydrogen at a pressure of 44.2 atm.

which, as has been observed by Dzhelepov et al.,[2] has a resonance nature, use of the result for λ_C obtained in the present work can decrease the value of the cross section by not more than 10%.

Figure 5 shows the dependence of the transfer rate λ_Z on the nuclear charge Z. It is clear from the figure that the experimental points are well approximated by the straight line $\lambda_Z \sim Z$. As has been shown by the calculations of Gershteĭn,[6] the mechanism of crossing of the molecular terms responsible for the transition gives a dependence close to that found experimentally if as the basis of the calculation we assume the condition

$$E_{p\mu} \ll 8 / Z^2, \quad (4)$$

i.e., if we assume that the energy of the $p\mu$ atom can be neglected in comparison with the value of the potential $V = -9Z^2/4R^4$ acting at large distances R of the muon from the nucleus Z. The cross section for the transfer (in mesic atom units) has the form

$$\sigma_{p\mu Z} = 3\pi \sqrt{\frac{2}{M}} \frac{Z}{v_{p\mu}} w_t, \quad (5)$$

where M is the reduced mass of the $p\mu$ atom and the nucleus Z, and w_t is the dimensionless transfer probability, which is weakly dependent on Z (for example, for oxygen $w_t = 0.32$).

In our experiments $E_{p\mu} = 0.025$ eV, and condition (4) is well satisfied for small Z. The transfer rate to carbon calculated from expressions (3) and (5) turns out to be $\lambda_Z^{theor} \approx 3 \times 10^{10}\ sec^{-1}$ and agrees with the experimental value. For large Z, condition (4) is no longer satisfied. For example, for the xenon nucleus $E_{p\mu} \gg 8/Z^2$. For this extreme the transfer cross section takes the form

$$\sigma_{p\mu Z} = \pi \lambda\!\!\!^{-2} w_t \quad (6)$$

and is almost independent of Z.

However, it must be noted that in derivation of expressions (4)—(6) we have actually not taken into account the screening of the nuclear charge by orbital electrons. Theoretical calculations and experimental data [2] show that the transfers occur preferentially to energy levels of the $Z\mu$

atom with a principal quantum number $n \approx Z$. For the xenon nucleus the mesic atom level $n_\mu = Z$ lies near the electronic level with $n_e = 3$. Therefore condition (4), with inclusion of the screening effect, will be less severely violated for heavy nuclei and for this reason the transfer cross section will be described by a dependence close to Eq. (5).

The transition rates from mesic hydrogen to nuclei reported in the present work, taken together with all of the characteristics of this process studied previously, are in satisfactory agreement with theory. The only exception is the results of two studies in which the transfer rate from dμ atoms to light nuclei was observed to be several times larger than from pμ atoms.[4–12] Dzhelepov[12] has shown that under the conditions of these experiments the energies of the dμ atoms considerably exceed the energies of the pμ atoms. Therefore the study of the transfer rate of muons from dμ atoms is interesting from the point of view of obtaining information on its dependence on the energy of the mesic atom.

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