

**Capture and transfer of stopped pions in alcohols**

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**Abstract**

The pion charge exchange probability in hydrogen for stopped  $\pi^-$  has been measured for a series of alcohols. The relative atomic capture probabilities for hydrogen in different chemical environments as well as for the other molecular constituents were extracted from the data using a phenomenological approach. The results allow the prediction of the charge exchange probability in other molecules of similar chemical structure. The charge exchange probability in deuterated methanols was measured and compared to the prediction of our model. A comprehensive picture is obtained if pion transfer from hydrogen to deuterium is included.

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## I. INTRODUCTION

In recent years much work has been devoted to the study of the capture of stopped negative pions in complex molecules. It is now well established that pion nuclear capture ratios depend not only on the nuclear charge of the atoms concerned but also depend strongly on the electronic environment in the molecule in which they are embedded.<sup>1-3</sup> This is understandable since the incident pion must pass through, and therefore interact with, the molecular electron cloud before passing into atomic orbitals near the nucleus from which nuclear capture predominantly occurs. However, the understanding of the precise way in which the molecular electrons affect the pion capture process is far from complete. Attempts to incorporate molecular effects into calculations of capture ratios in various kinds of molecule have met with partial success but fail to reproduce the experimental data satisfactorily in a number of cases.<sup>4</sup> Furthermore, there is continuing disagreement about the role of pion transfer from hydrogen onto heavier atoms. The generally accepted model favours collisional (external)  $\pi^-$  transfer by diffusion of a breakaway neutral  $\pi^-p$  system through the material followed by the transfer of the  $\pi^-$  in a collision with a Z atom<sup>1</sup> whereas the model proposed by D.F. Jackson<sup>5,6</sup> assumes  $\pi^-$  transfer by tunneling of the  $\pi^-$  along a bond between hydrogen and a neighboring heavier atom (internal transfer). In general molecular systems containing hydrogen atoms bonded to higher-Z atoms, these two modes of pion transfer are difficult to distinguish experimentally and the relative importance of the two modes is therefore still unclear. However, external transfer has been observed in mixtures of both H<sub>2</sub> and noble gases<sup>7</sup>, and CH<sub>4</sub> and noble gases.<sup>3</sup> Furthermore a recent experiment<sup>8</sup> has found evidence for external transfer in mixtures of hydrogenous and non-hydrogenous liquids.

The experimental data in this field generally fall into one of two categories: either capture ratios on atoms of different nuclear charge (usually obtained from pionic X-ray measurements) or charge exchange probabilities ( $\pi^-$ ,  $\pi^0$ ) (obtained from the  $\pi^0 \rightarrow 2\gamma$  signal following pion capture on hydrogen). In either case the main problem in interpreting the data is that the capture ratio or charge exchange probability is an average over the chemically different atoms of the same nuclear charge within the molecule. Isolating the changes in pion capture on atoms of a particular Z which may be due to molecular effects is thus a rather difficult task. The results of analyzing the data on charge exchange probabilities, for instance, to extract transfer parameters, often depend upon the particular model adopted to describe the initial pion capture on the different atoms within the molecule. Since this process itself is rather poorly understood, it would be useful in future work on pion chemistry if it were possible to establish an empirical scale of pion capture ratios on atoms in specific electronic environments. Such a scale would be analogous to the scale of chemical shifts which is derived from measurements of proton and <sup>13</sup>C NMR spectra. As in the case of the chemical shift scale, the position on the pion capture scale would be a function of the electron density around the capturing atom, especially the valence density to which the capture process appears to be particularly sensitive. Furthermore, since the nuclear capture rates are the net result of atomic capture followed by any transfer processes (if they occur), knowledge of the position of hydrogen atoms in different environments on the pion capture scale would be useful in extracting information on the pion transfer process.

In this paper we describe one approach to setting up such a pion capture scale and report the results of a recent experiment at TRIUMF in which the charge exchange

probability was measured for a series of alcohols. The results from the study are analyzed to yield relative capture rates on atoms in different chemical environments which are then interpreted in terms of simple ideas about the electronic environment in different regions of the molecule. We also report measurements of the pion charge exchange probability in the deuterated methanols  $CD_3OH$  and  $CH_3OD$  and compare these with the value for the non-deuterated isomer  $CH_3OH$ . An investigation of the effect of deuteration on the charge exchange probability in this system yields information on the nature of the process of pion transfer from hydrogen.

## II THEORY

We shall now outline the simple model first proposed by Smith.<sup>9,10</sup> One starts from the assumption that atoms of a given nuclear charge, which occur in similar chemical environments in the molecule but in different physical regions, have similar pion capture rates. The atomic capture probability (including all transfers) on an atom of nuclear charge  $Z_i$  in an environment labelled  $\alpha$  will be denoted  $R_{Z_i}^\alpha$ . If there are  $n_{Z_i}^\alpha$  such atoms in the molecule the capture ratio  $R(Z_i, Z_j)$  for the two atoms whose nuclear charges are  $Z_i$  and  $Z_j$  can be written

$$R(Z_i, Z_j) = \frac{\sum_{\alpha} n_i^{\alpha} R_{Z_i}^{\alpha}}{\sum_{\beta} n_j^{\beta} R_{Z_j}^{\beta}} \quad (1)$$

The summations are over all chemically different environments,  $\alpha$  and  $\beta$ , in which the  $Z_i$  and  $Z_j$  nuclei are found within the molecule. In general the choice of classifying atoms into chemically different groups will depend to some extent on the nature of the particular functional groups present within the molecule. Specific examples are given below.

Using this approach, the total nuclear capture probability,  $P_{Z_i}$ , for the nucleus  $Z_i$  becomes

$$P_{Z_i} = \frac{\sum_{\alpha} n_i^{\alpha} R_{Z_i}^{\alpha}}{\sum_{\alpha} n_i^{\alpha} R_{Z_i}^{\alpha} + \sum_{i \neq j} \sum_{\beta} n_j^{\beta} R_{Z_j}^{\beta}} \quad (2)$$

In this work, the observable of particular interest is the charge exchange reaction (CEX)



which occurs with a probability of  $\sim 60\%$  for  $\pi^{-}$  capture on hydrogen nuclei.<sup>11</sup> The observation of a  $\pi^0$  is an unambiguous signal for pions stopping in hydrogen, since - apart from  $\pi^{-3}He$  with  $\sim 15\%$ <sup>12,13</sup> - the charge exchange ( $\pi^{-}, \pi^0$ ) is suppressed ( $< 10^{-4}$ ) in any other  $\pi^{-}Z$ .<sup>14,15</sup> From Eq. (2) the total capture probability in hydrogen can be written as

$$W_H = \frac{\sum_{\alpha} n_H^{\alpha} R_H^{\alpha}}{\sum_{\alpha} n_H^{\alpha} R_H^{\alpha} + \sum_{i \neq j} \sum_{\beta} n_Z^{\beta} R_Z^{\beta}} \quad (4)$$

where the measured charge exchange probability  $P_{CEX}$  and  $W_H$  are related by  $P_{CEX} = 0.6 \times W_H$ . Suppose we consider a generalized molecule of the form



where X is some (polarizing) functional group such as  $-C=O$ ,  $-C=O_2H$ ,  $-OH$ ,  $-NH_2$  or  $-CH=CH(CH_2)_nCH_3$ . We expect that the carbon and hydrogen atoms which are located closest to the functional group X (environment  $\alpha$ ) and possibly the second neighbour ( $\beta$ ) may have electron densities which are somewhat different from those around the corresponding atoms in the non-polar side-chain  $CH_3(CH_2)_m$ . The pion capture rates on these  $\alpha$  (and  $\beta$ ) carbons and hydrogens may therefore differ significantly from those in the non-polar side-chain. However, because of the non-polar nature of the side-chain  $CH_3(CH_2)_m$ , the pion capture rates on all carbon atoms (or hydrogen atoms) within this group should be similar. On this basis, it should be possible to express the nuclear capture probability for a series of molecules of the same kind (that is with the same X group but different lengths of the side chain) in terms of a relatively small number ( $\sim 6$  for molecules of form (5)) of capture rates R.

Since it is the relative rather than absolute capture rates which are of primary interest, it would be convenient to define a standard capture rate on a particular reference nucleus in a specific electronic environment in terms of which all other capture rates could be expressed. In this respect, the capture rate on a carbon atom in a methylene or methyl group in a non-polar side-chain appears to represent a convenient choice for such an internal reference rate. These carbon-containing groups are commonly encountered in organic molecules and often occur in a side-chain which is isolated from the electron-distorting effects of other functional groups by several intervening carbon atoms. The electronic environment around such carbon atoms should not therefore differ significantly from one kind of molecule to another. The capture rate on one of these standard carbon atoms will be denoted  $R_C^S$ . If the charge exchange probabilities are known for a set of molecules with a common X but varying length side-chain, these can be fitted to give estimates of the capture ratios  $R_H^a/R_C^S$ ,  $R_H^\beta/R_C^S$ , and  $R_X/R_C^S$ .

A particular simple (and rather special) example of the above procedure will now be considered. When the functional group X corresponds to the hydrogen atom the molecular series is just the series of alkanes. The charge exchange probabilities for a number of different chain lengths have been measured previously by Petrukhin et al.<sup>16</sup> and Krumshtein et al.<sup>17</sup> and the results are summarized in Table I. (It should be noted that the values given in this table were normalized to a  $W_H$  value for polythene equal to  $(12.9 \pm 1.8) \times 10^{-3}$  which is the mean of three independent absolute measurements<sup>18-20</sup> and is slightly lower than the value quoted in ref.<sup>16</sup> The preferred value of  $12.9 \times 10^{-3}$  is used for consistency throughout this article in order to facilitate comparison of capture rates in different molecules). Since there is no polarizing group in the molecule one expects that all carbon atoms are essentially equivalent as far as pion capture is concerned (ignoring the slight difference between methyl and methylene groups). Similarly all hydrogens may be expected to be equivalent with respect to pion capture. The six values of  $W_H$  for molecules with formula  $C_{n_C}H_{n_H}$  can then be fitted with one hydrogen capture rate and one carbon capture rate using an expression of the form

$$W_H = \frac{n_H R_H}{n_H R_H + n_C R_C^S} \quad (6)$$

The data give a fit with a  $\chi^2$  per point of 1.0 for a ratio of  $R_H/R_C^S$  equal to  $(6.26 \pm 0.08) \times 10^{-3}$ . The reasonable fit for these data with just one adjustable parameter

confirms the assumption of the equivalence of the different carbon (and hydrogen) atoms in the molecular series with respect to pion capture. The capture ratio  $R_H/R_C^S$  obtained from the alkane series agrees with the pion capture probability in hydrogen for polythene, i.e.  $W_H(\text{CH}_2) \approx 2 \times R_H/R_C^S$  (see Table I). The calculated values for the alkanes are listed in the last column of Table I using Eq. (6). The agreement with the measured values is good. It is interesting to note that the apparent constancy of the ratio  $R_H/R_C^S$  for the molecular series in Table I and for polythene shows that the capture ratio is phase independent since this group of molecules contains gases, liquids and solids. Since the capture rate on hydrogen is the net result of atomic capture followed by transfer we are led to the conclusion that if transfer is significant then the transfer rate is independent of the phase in which the molecule is present.

In Table I the pion capture probability for propane is calculated in the absence of an experimental value. This is a very useful information because it can be compared with the capture probability by hydrogen in propane for kaons and antiprotons available from bubble chamber studies. For kaons we have the results of van der Velde-Wilquet et al of  $4.0 \pm 0.4\%$ <sup>21</sup> and of Murphy et al. of  $3.2 \pm 0.4\%$ <sup>22</sup>, which have to be compared with 1.6% for pions. The results are close yet the values for kaons are significantly higher than for pions indicating that kaons do not exhibit such a strong suppression of absorption by the hydrogen. For antiprotons the value of  $11 \pm 3\%$  was found by Pawlewicz et al.<sup>23</sup> again higher than for kaons. The trend is quite clear and speaks for itself, although further confirmation of these data would be important.

For a more general molecular series of the kind  $\text{CH}_3(\text{CH}_2)_m\text{CH}_2\text{CH}_2\text{X}$ , it may be necessary to use two or three unknown hydrogen ratios  $R_H/R_C^S$ , one or two carbon ratios  $R_C/R_C^S$  and one or more additional ratios to describe capture in the X group. In this case one requires values for  $W_H$  in five or more different members of a homologous series in order to extract useful estimates of the capture ratios. This has provided the motivation for the present experimental study of charge exchange probabilities in a series of alcohols as well as for an earlier study on acid anhydrides.<sup>9</sup>

### III EXPERIMENTAL TECHNIQUE AND DATA ANALYSIS

The experiment was performed in the M13 low-energy pion channel at TRIUMF. The set-up used in this experiment is very similar to that described in detail elsewhere.<sup>24</sup> A beam of 78 MeV/c pions was stopped in a target holder containing the liquids. A coincidence of signals from three plastic scintillation counters S1, S2, and S3 defined a beam particle and an anti-coincidence with a scintillation counter S4 (i.e. 1234) behind the target signalled the stopping of the particle in the target. In order to eliminate the  $\pi^0$  background from  $\pi^-$  stopping in S3, this counter was made of deuterated scintillator. If a stopped  $\pi^-$  is captured by a proton in hydrogen, then a  $\pi^0$  is produced 60% of the time. The decay  $\gamma$ -rays from the  $\pi^0$  were detected using a  $\pi^0$  spectrometer consisting of 2 large NaI crystals TINA ( $\phi 46 \text{ cm} \times 51 \text{ cm}$ ) and MINA ( $\phi 36 \text{ cm} \times 36 \text{ cm}$ ). Each NaI was kept at a distance of  $\sim 80 \text{ cm}$  from the target in order to be able to distinguish between neutrons and  $\gamma$ -rays using the time-of-flight technique. Charged particles entering TINA and MINA were rejected by plastic scintillation counters in front of the two NaI detectors.

The purity of the chemicals used for the present experiment exceeded 99 %. All targets used in this experiment were contained in cylindrical target holders,  $\phi 133 \text{ mm} \times 15.5 \text{ mm}$ , with  $25 \mu\text{m}$  thick stainless steel windows. The fraction of incident

pions stopping in the target windows was determined by measuring the pion stops as a function of target thickness. For this purpose various thicknesses of CH<sub>2</sub> were used as target material. The fraction of pions stopping in the windows turned out to be less than 3%. The beam momentum was selected to optimize stopping in the liquid target.

A histogram of  $E_T \cdot E_M$ , where  $E_T$  is the energy deposited in TINA and  $E_M$  is the energy deposited in MINA, was generated to determine the  $\pi^0$  yield,  $N_{\pi^0}$ . Since

$$E_T \cdot E_M = \frac{M_{\pi^0}^2}{4 \sin^2 \frac{\psi}{2}} \quad (7)$$

where  $M_{\pi^0}$  is the mass of the  $\pi^0$  and  $\psi$  is the angle between the two  $\gamma$  rays, the  $\pi^0$  events show up as a peak in this histogram (see ref.<sup>24</sup> for a figure). The number of  $\pi^0$  produced in each target was determined by fitting a function

$$f(E) = A \cdot \exp\left(\frac{E-B}{D}\right) \left[1 - \operatorname{erf}\left(\frac{E-B}{C}\right)\right] + Bg \quad (8)$$

where  $E = E_T \cdot E_M$  and  $Bg$  is a background term.  $A$ ,  $B$ ,  $C$  and  $D$  are amplitude, energy and width related parameters.<sup>24</sup> Integration of the  $\pi^0$  peak above the background gave  $N_{\pi^0}$ .

The number of  $\pi^-$ s stopping in the target,  $N_{\pi^-}$ , was obtained using the technique described in ref.<sup>24</sup> The relative charge exchange probability for each concentration was obtained as  $N_{\pi^0}/N_{\pi^-}$  and was then normalized to that measured in CH<sub>2</sub>. The stability of the data was checked by repeating the measurements with CH<sub>2</sub> at regular intervals.

The pion capture probability in hydrogen,  $W_H$ , for each target was calculated from

$$W_H(\text{Target}) = W_H(\text{CH}_2) \times \frac{T(\text{Target})}{T(\text{CH}_2)} \quad (9)$$

where  $W_H(\text{CH}_2)$  is the pion capture probability for polythene and  $T(\text{Target})$  is the ratio of  $N_{\pi^0}/N_{\pi^-}$  for a particular target.  $T(\text{CH}_2)$  was calculated from the mean of 17 measurements made at regular intervals during the course of the present experiment. The value for  $W_H(\text{CH}_2)$  was taken to be  $(12.9 \pm 1.8) \times 10^{-3}$ . In calculating the errors of the  $W_H$  values, only the errors in  $T(\text{Target})$  and  $T(\text{CH}_2)$  were taken into account. The error in  $W_H(\text{CH}_2)$  was not included since it is the relative  $W_H$  values which are of primary interest.

#### IV RESULTS

The values of  $N_{\pi^0}$  and  $W_H$  calculated by means of Eq. (9) for the different targets are listed in Table II. The  $W_H$  values for the primary alcohols and water are plotted against the number of carbon atoms in the molecule,  $n_C$ , in Figure 1 and show a monotonic rise with  $n_C$ . The  $W_H$  values for this alcohol series asymptotically approach the value  $W_H(\text{CH}_2)$  which is indicated as a straight line. The charge exchange probabilities for all the primary alcohols (excluding the deuterated methanols) and water were fitted with an expression of the form

$$W_H = \frac{n_H^\alpha R_H^\alpha + R_H^O + n_H^\beta R_H^\beta}{n_H^\alpha R_H^\alpha + R_H^O + n_H^\beta R_H^\beta + n_C R_C + R_O} \quad (10)$$

Here  $R_H^\alpha$  is the rate for pion capture on a hydrogen atom bound to a carbon atom which is in the  $\alpha$  position with respect to the OH group.  $R_H^O$  is the rate for pion capture on a hydrogen atom of the OH group.  $R_H^\beta$  is the rate for pion capture from all other hydrogen atoms.  $R_C$  is the rate for pion capture on a carbon atom and  $R_O$  is the rate for pion capture on an oxygen atom. The  $n_H$  and  $n_C$  factors are the relative numbers of the respective atoms in the given molecule.

Two fits of the data were performed, each with slightly different data samples. In both cases the deuterated methanols were excluded from the fits as pion transfer from hydrogen to deuterium complicates the situation there. We shall address this problem later. In fit I only the primary alcohols plus water were included, whereas in fit II all the alcohols from Table II plus water were employed. The values of the best fit capture ratios (relative to  $R_C$ ) are given in Table III. The result of fit I gives a  $\chi^2$  per point of 0.77 and will be discussed first. The result for  $R_H^\beta/R_C$ , the capture ratio for hydrogen atoms far from the polarizing OH group, is  $(6.72 \pm 0.05) \times 10^{-3}$  which is a little higher than the value for the alkanes of  $R_H/R_C^S = (6.26 \pm 0.08) \times 10^{-3}$ . The alcohol result gives  $(13.44 \pm 0.10) \times 10^{-3}$  for polythene, which is satisfactory though not perfect. The value for  $R_H^\alpha/R_C$ , the capture ratio for hydrogen atoms bound to carbon which is in  $\alpha$  position to the OH group is  $(6.28 \pm 0.08) \times 10^{-3}$ , slightly lower than the value of  $R_H^\beta/R_C$ . This is consistent with the lower electron density expected around hydrogen atoms of a methylene group adjacent to a hydroxyl group due to the strongly electronegative character of the oxygen atom. Since the atomic capture process is thought to be dominated by Auger transitions, the capture rate on an atom is expected to be a function of the electron density around that atom. The value for  $R_H^O/R_C$ , the capture ratio for a hydrogen atom in an OH group is significantly less than both  $R_H^\beta/R_C$  and  $R_H^\alpha/R_C$ . This is consistent with the significant reduction in electron density around a hydrogen atom attached directly to an electronegative oxygen atom. Inclusion of  $W_H$  for  $H_2O$  is crucial for the fit because it largely determines  $R_H^O/R_C$ . If  $W_H(H_2O)$  is discarded then  $R_H^O/R_C$  is compatible with 0 and the overall errors for the fit are much worse. Finally, the ratio  $R_O/R_C$  is in agreement with other values reported for O/C capture ratios in hydroxyl-containing molecules such as saccharides.<sup>9</sup> The quality of the fit becomes evident if  $W_H$  is calculated using Eq.(10) with the parameters given in Table III. The calculated values are listed in the last column of Table II and agree with the measurement very well except for the deuterated methanols, which will be discussed below in more detail, and cyclohexanol where the calculation is  $\sim 15\%$  higher than the measurement. The ring structure of this molecule might change the electron distribution in a manner such that the applicability of our model is limited. However, no effect of the ring structure was found for the alkanes hexane and cyclohexane as can be seen from Table I and the only difference is that cyclohexanol contains a polarizing functional group. Hence we are left with a slight puzzle whether the observed suppression of  $W_H$  is real and due to the ring structure or whether an experimental error is introduced by the (claimed) impurity of the chemical cyclohexanol or a misbehaviour of the apparatus. The location of the hydroxyl group (Butan-1-ol and Butan-2-ol) seems not to influence the  $W_H$  values very much which is confirmed by the calculation. Also the calculation for 2-methylpropan-2-ol, which has a fairly different structure than the primary alcohols, is very close to the measurement.

The result of fit II gives a  $\chi^2$  per point of 6.7. The quality of this fit is worse as manifested by the  $\chi^2$  and the error bars of the capture ratios. However, the general

trend of the fit II is the same as for fit I and the results agree within the error bars. The difference is caused by the inclusion of  $W_H$  for cyclohexanol in fit II, where fit I fails to predict the capture probability on hydrogen atoms satisfactorily as mentioned above. We recommend fit I for use in predicting  $W_H$  values for alcohols of similar chemical structure as the primary alcohols. The error bars, however, given for fit I in Table III are strictly valid only for primary alcohols. The error bars of fit II give an idea of what the error bars for alcohols of similar structure are.

The model fits the data well and seems a reasonable approach. The interpretation was confirmed with an alternative technique, using deuterated methanols. Thus we measured the hydrogen capture probability for  $CD_3OH$ ,  $CH_3OD$ , and  $CH_3OH$ . The results for  $W_H$  are given in Table IV. The interesting observation is that the sum of capture probabilities in  $CD_3OH$  and  $CH_3OD$  falls short of the probability for  $CH_3OH$ . The same conclusion can be drawn if the individual values  $W_H$  for  $CD_3OH$  and  $CH_3OD$  are compared with the calculated results obtained from the alcohol series which are presented in the last column of Table IV. However, we can correct for pion transfer from hydrogen to deuterium ( $\pi^- p + d \rightarrow \pi^- d + p$ ) which we investigated recently in  $H_2/D_2$  gas mixtures<sup>24</sup> (purely external transfer) and in  $H_2O/D_2O$  liquid mixtures<sup>25</sup> as a function of the deuterium concentration. If we assume equal stopping probabilities in hydrogen and deuterium we apply the external transfer correction as measured in the gas mixtures. The relative deuterium concentration for  $CD_3OH$  and  $CH_3OD$  is 3 and 1/3 respectively. The corresponding figures for pion transfer at these concentrations were obtained from ref.<sup>24</sup> and amount to  $Q \sim 27\%$  transfer for  $C_d/C_p=3$  and  $Q \sim (10 - 13)\%$  transfer for  $C_d/C_p=1/3$ . The corrected pion capture probabilities for  $CD_3OH$  and  $CH_3OD$  were obtained by calculating  $W_H(\text{exp})/(1-Q)$  and are listed in the next column of Table IV as well as the sum of both. This is a significant improvement over the measurement. The corrected values agree almost with the prediction from the alcohol series as well as with the measurement of  $W_H(CH_3OH)$ . To include also the effect of the preference of pions for the deuterium in the initial capture choice we corrected using the "transfer" probabilities for  $H_2O/D_2O$ , resulting in  $Q \sim 36\%$  transfer for  $C_d/C_p=3$  and  $Q \sim 11\%$  transfer for  $C_d/C_p=1/3$ . The results listed in the third column of Table IV are slightly higher than the ones in the second column but are comparable. The agreement is very satisfactory and supports the whole approach.

## V CONCLUSIONS

The pion capture probabilities for the series of alcohols reported here were analyzed in terms of a simple model of pion capture on atoms in different chemical environments. The model yields values for the relative capture ratios hydrogen/carbon and oxygen/carbon which are consistent with the known electron distribution in the molecule and with other data on atomic capture ratios. This method of analysis can be applied to systems where charge exchange probabilities are known for a homologous series of molecules. The (empirical) capture ratios obtained by this method could be used to predict the charge exchange probabilities in other molecules containing similar functional groups.

The result of the alcohol series was applied to investigate deuterated methanols. It is found that the pion capture probability for  $CD_3OH$  and  $CH_3OD$  is smaller than the prediction of the model and the  $W_H$  values for  $CD_3OH$  and  $CH_3OD$  do also not add up to  $W_H(CH_3OH)$ . However, if the measured  $W_H$  values are corrected for



pion transfer from hydrogen to deuterium in collisions  $\pi^- p + d$  as obtained from our previous studies<sup>24,25</sup> then overall agreement is achieved. This is strong evidence that collisional pion transfer takes place in these organic compounds and at the same time a verification of the usefulness of the model.

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Table I Pion capture probabilities in hydrogen for alkanes. The data are taken from Petrukhin et al. (ref. 16) and Krumshtein et al. (ref. 17) renormalized to  $W_H(\text{CH}_2) = 12.9 \times 10^{-3}$ . In the last column the calculated values are presented using Eq.(6) with the parameter given in the text.

Molecule	Formula	$W_H$ ( $10^{-3}$ )	Calculated ( $10^{-3}$ )
Methane	$\text{CH}_4$	$24.73 \pm 0.53$	$24.42 \pm 0.30$
Ethane	$\text{CH}_3\text{CH}_3$	$18.77 \pm 0.53$	$18.42 \pm 0.23$
Propane	$\text{CH}_3\text{CH}_2\text{CH}_3$		$16.41 \pm 0.21$
Pentane	$\text{CH}_3(\text{CH}_2)_3\text{CH}_3$	$14.15 \pm 0.49$	$14.79 \pm 0.19$
Hexane	$\text{CH}_3(\text{CH}_2)_4\text{CH}_3$	$14.77 \pm 0.48$	$14.39 \pm 0.18$
Dodecane	$\text{CH}_3(\text{CH}_2)_{10}\text{CH}_3$	$13.52 \pm 0.62$	$13.37 \pm 0.17$
Heptadecane	$\text{CH}_3(\text{CH}_2)_{15}\text{CH}_3$	$12.46 \pm 0.46$	$13.08 \pm 0.16$
Cyclohexane	$\text{C}_6\text{H}_{12}$	$12.72 \pm 0.49$	$12.36 \pm 0.16$
Polythene	$(\text{CH}_2)_n$	$12.90 \pm 0.36$	$12.36 \pm 0.16$

Table II Pion capture probabilities in hydrogen for alcohols (present data). In the last column the calculated values are presented using Eq.(10) and the parameters of fit I given in Table III.

Molecule	Formula	$N_{\nu}$	$W_H$ ( $10^{-3}$ )	Calculated ( $10^{-3}$ )
Water	$\text{H}_2\text{O}$	3802	$3.52 \pm 0.07$	$3.52 \pm 0.05$
Methanol	$\text{CH}_3\text{OH}$	10438	$7.47 \pm 0.09$	$7.47 \pm 0.10$
Ethanol	$\text{CH}_3\text{CH}_2\text{OH}$	4305	$8.88 \pm 0.16$	$9.04 \pm 0.08$
Propan-1-ol	$\text{CH}_3(\text{CH}_2)_2\text{OH}$	5975	$9.98 \pm 0.17$	$9.90 \pm 0.07$
Butan-1-ol	$\text{CH}_3(\text{CH}_2)_3\text{OH}$	6838	$10.70 \pm 0.17$	$10.47 \pm 0.08$
Pentan-1-ol	$\text{CH}_3(\text{CH}_2)_4\text{OH}$	6569	$10.95 \pm 0.18$	$10.87 \pm 0.08$
Hexan-1-ol	$\text{CH}_3(\text{CH}_2)_5\text{OH}$	6565	$11.03 \pm 0.18$	$11.17 \pm 0.08$
Heptan-1-ol	$\text{CH}_3(\text{CH}_2)_6\text{OH}$	5796	$11.29 \pm 0.19$	$11.41 \pm 0.08$
Octan-1-ol	$\text{CH}_3(\text{CH}_2)_7\text{OH}$	7211	$11.54 \pm 0.17$	$11.59 \pm 0.08$
Decan-1-ol	$\text{CH}_3(\text{CH}_2)_9\text{OH}$	5160	$11.96 \pm 0.22$	$11.87 \pm 0.08$
Deuterated Methanol	$\text{CD}_3\text{OH}$	807	$0.845 \pm 0.031$	$1.17 \pm 0.02$
Deuterated Methanol	$\text{CH}_3\text{OD}$	3884	$5.55 \pm 0.11$	$6.31 \pm 0.10$
Butan-2-ol	$\text{CH}_3\text{CH}_2\text{CH}(\text{OH})\text{CH}_3$	7471	$10.85 \pm 0.17$	$10.54 \pm 0.08$
2-Methyl-propan-2-ol	$(\text{CH}_3)_3\text{COH}$	6256	$10.66 \pm 0.18$	$10.61 \pm 0.09$
Cyclohexanol	$(\text{CH}_2)_5\text{CHOH}$	3143	$8.23 \pm 0.18$	$9.57 \pm 0.07$

Table III Best fit capture ratios for alcohols. Fit I and II are described in the text.

Capture Ratio	Fit I	Fit II
$R_H^B/R_C$	$(6.72 \pm 0.05) \times 10^{-3}$	$(6.53 \pm 0.12) \times 10^{-3}$
$R_H^a/R_C$	$(6.28 \pm 0.08) \times 10^{-3}$	$(5.90 \pm 0.34) \times 10^{-3}$
$R_H^O/R_C$	$(3.48 \pm 0.07) \times 10^{-3}$	$(3.11 \pm 0.31) \times 10^{-3}$
$R_O/R_C$	$1.97 \pm 0.02$	$1.76 \pm 0.17$

Table IV Pion capture probabilities in hydrogen for deuterated methanols (all in units of  $10^{-3}$ ). The calculated values in the last column are obtained by using Eq.(10) and the parameters of fit I given in Table III.

Molecule	$W_H(\text{exp})$	Corrected ( $H_2/D_2$ )	Corrected ( $H_2O/D_2O$ )	Calculated (Alcohol series)
$CD_3OH$	$0.845 \pm 0.031$	1.15	1.33	$1.17 \pm 0.02$
$CH_3OD$	$5.55 \pm 0.11$	6.27	6.24	$6.31 \pm 0.10$
$CH_3OH$	$7.47 \pm 0.09$	7.42	7.57	$7.47 \pm 0.10$

FIGURE CAPTIONS

Fig. 1 Pion capture probabilities in hydrogen,  $W_H$ , of alcohols and water.  $W_H$  for  $CH_2$  is indicated with a straight line. The solid curve is a spline fit through the fitted values.

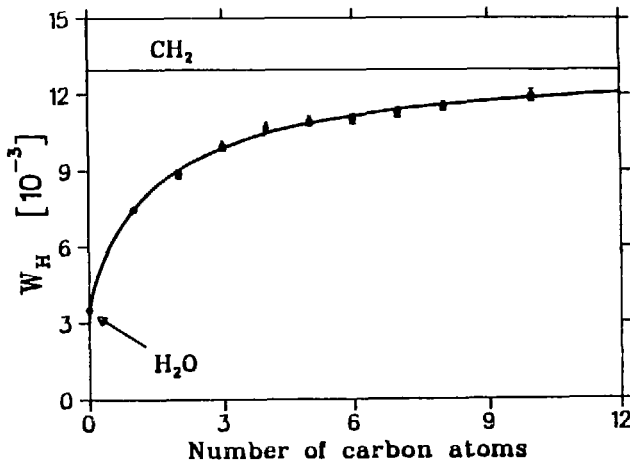


Fig. 1