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The probability W of nuclear π^- capture on bound hydrogen atoms

$$\pi^- + <p>_{Z_m H_n} \rightarrow n + \pi^0 \qquad (1)$$

is strongly suppressed as compared to that of the capture on free hydrogen

$$\pi^- + p \rightarrow n + \pi^0 \qquad (2)$$

and depends upon the chemical bond Z–H [1]. This fact has been explained by the model of large mesic molecules [2] according to which the probability W has been determined by the following expression

$$W = W_{model} = \frac{aZ^{-2}}{mZ + n}, \qquad (3)$$

where a is an empirical coefficient describing the peculiarities of the chemical coupling Z–H in the $Z_m H_n$ molecule.

The effect of the chemical bond properties of hydrogen on the nuclear capture rate (1) in various hydrogen compounds has been observed, e.g., in refs. [3–5] where the experimental dependence of the coefficient upon acid strength [3], induction constants [4] and autoprotolysis constants [5] have been obtained.

Our previous work [6] has established the mechanism of the suppression of nuclear capture (1), i.e., that of negative pion transfer to Z atoms in hydrogeneous chemical substances $Z_m H_n$ and $Z'_m H_n$+Z mixtures

$$<p\pi^-> + Z \rightarrow Z\pi^- + p. \qquad (4)$$

This mechanism is an additional one to the scheme of processes considered in the model of large mesic molecules.

According to ref. /6/ the probability of negative pion transfer to hydrogen atoms in binary compounds Z_mH_n is determined by the following expression

$$W = W_{model} \cdot q, \quad q = \frac{1}{1 + <\Lambda_Z> \epsilon_Z}, \qquad (5)$$

where q is the suppression of nuclear capture (1) due to transfer (4), $\epsilon_Z = \frac{m}{n}$ is the "concentration" of the atoms Z in the substance Z_mH_n, $<\Lambda_Z>$ is the transfer constant for reaction (4). This means that for reliable separation of the "chemical" effects in nuclear negative pion capture on bound hydrogen, it is necessary to take into consideration quantitatively the transfer in the suppression of the probability W. At present the transfer of negative pions in the mixtures of free hydrogen with other atoms, in mechanical mixtures H_2+Z /7/ is sufficiently well studied. However, the results of experiments /7/ are not to be used directly for taking into consideration the negative pion transfer in hydrogen compounds since according to ref. /6/ the transfer intensity in H_2+Z mixtures and in the systems Z'_mH_n+Z differs considerably.

The present investigation has been performed to study process (4) observed in our previous experiment for clearing out the nature of its difference from the process $p\pi^- + Z \to Z\pi^- + p$. For this purpose the negative pion transfer to carbon atoms has been compared in pure methane, ethane, ethylene and in their mixtures with hydrogen. Since in the mixtures $H_2 + C_mH_n$ the basic fraction of hydrogen mesic atoms is produced on free hydrogen it appears possible to separate the transfer channel

$$p\pi^- + <C>_{C_mH_n} \to C_{\pi^-} + p \qquad (6)$$

and compare its intensity with that of the process

$$<p\pi^-> + <C>_{C_mH_n} \to C_{\pi^-} + p, \qquad (7)$$

which takes place in chemical compounds of type C_mH_n. The experiment was performed by using the 80 MeV negative pion beam from the Dubna synchrocyclotron. The experimental procedure is similar to that described earlier /8/.

Negative Pion Transfer in the Series of Saturated Hydrocarbons

In the series of similar compounds, e.g., saturated hydrocarbons C_mH_n the character of chemical bond C–H is not changed when passing from one compound to the other. Therefore, the coefficients a calculated by the experimental values of the probability W according to formula (3) should have equal values for all C_mH_n molecules. The presence of negative pion transfer to carbon creates the dependence of the coefficients a upon the concentration of carbon atoms on these molecules. This dependence shows the intensity of process (7).

Gaseous hydrocarbons CH_4, C_2H_6 and C_2H_4 were frozen in hermetically sealed vessels of stainless steel and were exposed to the negative pion beam in styrofoam cryostat filled with liquid nitrogen. Measurements with a vessel filled with gaseous hydrogen were performed in the same conditions and with a polyethylene, $(CH_2)_n$ target of the same dimensions.

The W probability for the organic compounds were normalized to the yield of reaction (2) from H_2. Table I presents the values of the probabilities W, the coefficients a and the atomic concentrations of hydrogen for all the compounds used in our experiment.

As is seen from Table I, the coefficient a within the measurement error is monotonously decreased with increasing carbon concentration in the C_mH_n molecules of both series. At the same time when passing from polyethylene and cyclohexane to ethylene having another

type of chemical bounds with the same ϵ-value, the coefficient a similarly to previous observations [1] is changed by a jump. Turning from the saturated hydrocarbons to the unsaturated ones means changing the sp^3 orbitals establishing the C–H bond into sp^2 ones. This transition results in a more electronegative carbon atom and thus in the suppression of the probability W, as well.

Table 1

Compounds C_mH_n	$W, 10^{-3}$	$\varepsilon = m/n$	a
CH_4	27.80±0.60	0.25	2.50 ± 0.05
C_2H_6	21.10±0.60	0.33	2.28 ± 0.06
C_5H_{12}	15.90±0.55 [9]	0.42	
C_6H_{14}	16.60±0.54 [9]	0.43	2.06 ± 0.05
$C_{12}H_{26}$	15.20±0.70 [9]	0.46	
$C_{17}H_{36}$	14.00±0.52 [9]	0.47	1.98 ± 0.06
$(CH_2)_n$	14.50±0.40	0.5	
C_6H_{12}	14.30±0.55 [9]	0.5	2.07 ± 0.05
C_2H_4	9.87±0.30	0.5	1.42 ± 0.04
C_6H_6	3.90±0.30 [9]		0.98 ± 0.08
$C_{12}H_{10}$	2.76±0.31 [9]		0.82 ± 0.09
$C_{18}H_{14}$	2.76±0.31 [9]		0.88±0.09
$C_{10}H_{18}$	2.00±0.15 [9]		0.61 ± 0.05

After renormalizing the coefficient a for the compounds of the unsaturated series, the dependence $a(\epsilon)$ was approximated by formula (7)

$$a = \frac{A}{1 + \langle \Lambda_c \rangle \frac{m}{n}}, \qquad (8)$$

where A is a renormalized value of the coefficient a, free of the transfer effect, $\langle \Lambda_c \rangle$ is the constant of the negative pion transfer to carbon $\langle C \rangle_{C_mH_n}$. The following results have been obtained

$$\langle \Lambda_c \rangle = 1.6 \pm 0.2, \qquad (9)$$

$$A = 3.54 \pm 0.17.$$

The constant $\langle \Lambda_c \rangle = 1.6 \pm 0.2$ obtained by studying the transfer effect in the simplest case in the series C_mH_n coincides within errors with $\langle \Lambda_c \rangle = 1.0 \pm 0.4$ obtained by studying that in the gaseous mixtures $CH_4 + Ar$, $C_2H_4 + Ar$ and the liquids $C_{10}H_{22} + CCl$ and $C_6H_6 + CCl$ [6]. By the phenomenological model the constant $\langle \Lambda_c \rangle$ is equal to the proportion ratio of transfer (7) and de-excitation resulting in transfer (1) in mesic atom collisions with bound hydrogen. The closeness of $\langle \Lambda_c \rangle$ to unity means that the processes transfer (7) and de-excitation resulting in transfer (7) for the mesic atoms produced in the $Z H$ molecule dissociation have equal rates.

Negative Pion Transfer in Gaseous Mixtures $H_2 + C_mH_n$

In the $H_2 + C_mH_n$ mixtures two types of hydrogen mesic atoms are produced: $p\pi^-$ are produced on free hydrogen and $\langle p\pi^- \rangle$ on bound hydrogen. As has been shown earlier [7], the transfer is due to the hydrogen mesic atom collisions with heavy atoms. It is necessary in $H_2 + C_mH_n$ mixtures along with the above transfer processes (6) and (7) to take into consideration de-excitation of hydrogen mesic atoms in collisions both with H_2 molecules and with C_mH_n molecules due to the hydrogen present in the latter. In a general form for the $H_2 + C_mH_n$ mixture

$$W(H_2 + \epsilon X) = q + \epsilon \frac{W_X}{\langle q_X \rangle} \langle q \rangle \frac{B_X}{B_H}, \qquad (10)$$

where B_X and B_H are the stopping powers of the hydrogen atom and the X molecules, ϵ is the molecular concentration of hydrocarbon in the mixture, $W_X / \langle q_X \rangle$ is the probability of $\langle p\pi^- \rangle$ mesic atom production in the mixture, q and $\langle q \rangle$ are suppressions of nuclear capture (2) to (1) in the $H_2 + C_mH_n$ mixture caused by processes

(6) and (7), respectively. The values of $\langle q_x \rangle = \frac{a_x}{A}$ for methane, ethane and ethylene were determined according to the data of Table I by using formula (9) and were found to be:

$$\langle q_{CH_4} \rangle = 0.72 \pm 0.03, \quad \langle q_{C_2H_6} \rangle = 0.65 \pm 0.03, \quad \langle q_{C_2H_4} \rangle = 0.56 \pm 0.04.$$

In the presentations of the phenomenological model /7/ for the $H_2 + C_m H_n$ mixtures

$$q = \frac{1 + \kappa\epsilon}{1 + (\Lambda + \kappa)\epsilon}, \quad \langle q \rangle = \frac{1 + \langle \kappa \rangle \epsilon}{1 + (\langle \kappa \rangle + \langle \lambda \rangle)\epsilon}, \qquad (11)$$

where Λ and κ are the constants of transfer (6) and de-excitation of the $p\pi^-$ atom in its collision with $C_m H_n$ molecules resulting in nuclear pion capture by the proton; $\langle \Lambda \rangle$ $\langle \kappa \rangle$ and the same for the $\langle p\pi^- \rangle$ mesic atom. In the experiments the probability W was determined for all organic gases $C_m H_n$ and $W(H_2 + \epsilon X)$ for the mixtures $H_2 + CH_4$, $H_2 + C_2H_6$ of various concentrations. The obtained results are presented in Table 2. Here the values of the constants are given for one proper atom of the $C_m H_n$ molecules. The constants $\langle \Lambda \rangle$ and $\langle \kappa \rangle$ are poorly determined by our data, therefore Table 2 presents only their sums. Within measurement errirs the constants of negative pion transfer from free hydrogen to carbon of $C_m H_n$ molecules is similar for the carbon atom being on methane and ethylene: $\langle \Lambda_c \rangle = 4.6 \pm 0.3$ and coincides with the value $\Lambda_c = 5.0 \pm 0.5$ which can be obtained by interpolating the data for $H_2 + Z$ mixtures (where Z: He , Ne , Ar , Kr , Xe) /10/ within the same range of carbon concentration. This means in particular that with respect to $p\pi^-$ -mesic atoms carbon atoms in the $C_m H_n$ molecules behave as free, and hence, the size of $p\pi^-$ -mesic atom is considerably smaller than that of the carbon atom.

By our estimation the de-excitation constant for all the three types of hydrocarbons studied is similar, $\kappa_{\langle P \rangle} \sim 0.3$.

Table 2

Mixture $H_2 + C_m H_n$	Range of variation of molecular concentration of hydrocarbon in the mixture	$\frac{\Lambda_c}{\Lambda_{C_m H_n}/m}$	$\frac{\langle \kappa \rangle}{\kappa_{C_m H_n}/n}$	$\langle \Lambda_c \rangle + \langle \kappa \rangle$
$H_2 + CH_4$	0.1-1.6	6.0±0.8	0.3±0.2	1.3±5.0
$H_2 + C_2H_6$	0.04-2.2	4.5±0.4	0.4±0.1	0.6±0.4
$H_2 + C_2H_4$	0.03-0.6	4.4±0.4	0.2±0.1	0.1±0.3
Mean values		4.6±0.3	0.3±0.1	

This means that bound hydrogen about three times less effectively takes part in $p\pi^-$-mesic atom de-excitation than the free one. The considerable decrease of the constant of transfer to carbon ($\langle \Lambda_c \rangle = 1.6 \pm 0.2$) for $p\pi^-$ -mesic atoms produced on bound hydrogen comparing to the constant $\Lambda_c = 4.6 \pm 0.3$ for $p\pi^-$ -mesic atoms, apeears to be due to the excitation of $p\pi^-$ -mesic atoms at the moment of their production. In this case both the transfer cross section and its lifetime are decreased since the size of the mesic atom is proportional to $\sim n^2$ /1/ and the rate of nuclear negative pion transfer to proton in the mesic atom is about $\Gamma_{ns} \sim 1{,}1 \cdot 10^{15}/n^3$. Present results contradict the conceptions developed in ref. /11/ according to which the production of $\langle p\pi^- \rangle$ -mesic atoms in hydrogen compounds is assumed to take place in the highly excited states with the basic quantum number $n \sim 30 - 70$.

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