# Interception of $\pi^-$ mesons by carbon atoms in organic molecules

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It is established that the intensity of $\pi^-$-meson interception by carbon in organic molecules $C_mH_n$ differs in the hydrocarbon series from that in the gas mixtures $H_2+C_mH_n$. It is suggested that this difference is due to the different excitation energies of the hydrogen mesic atoms produced on the free ($H_2$) and on the chemically bound (Z–H) hydrogen. The grouping of the atoms Z into molecules, their surrounding by hydrogen atoms, and singularities in the chemical bonds of the Z atoms exert on noticeable influence on the interception.

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The probability W of nuclear capture of $\pi^-$ mesons by bound hydrogen

$$\pi^-+\langle p\rangle_{Z_mH_n}\to n+\pi^0 \tag{1}$$

is greatly suppressed in comparison with capture by free hydrogen

$$\pi^-+p\to n+\pi^0 \tag{2}$$

and depends on the peculiarities of the Z—H chemical bond.[1] This fact was explained in the large-mesic-molecule model,[2] according to which W is given by

$$W=W_{\text{mod}}=\frac{naZ^{-2}}{mZ+n}, \tag{3}$$

where a is an empirical coefficient characterizing the singularities of the Z—H chemical bond in the molecule $Z_mH_n$.

The influence of the singularities of the chemical bond of hydrogen on the nuclear capture probability (1) in various hydrogen-containing compounds was established, for example, in[3-5], where experimental data were obtained for the dependence of the coefficient a on the acid strengths,[3] induction constants,[4] and autoprotolysis constants.[5]

In our preceding study[6] we established a mechanism, supplementing the scheme of processes considered in the large-mesic-molecule model, for the suppression of the nuclear capture (1), namely the interception of the $\pi^-$ mesons by the atoms Z in the hydrogen-containing chemical substances $Z_mH_n$ and in the mixtures $Z'_mH_n$ + Z

$$\langle p\pi^-\rangle+Z\to Z\pi^-+p. \tag{4}$$

According to[6], the probability of nuclear capture of $\pi^-$ mesons by hydrogen in binary $Z_mH_n$ compounds is given by the expression

$$W=W_{\text{mod}}\langle q\rangle,\quad \langle q\rangle=\frac{1}{1+\langle\Lambda_Z\rangle\varepsilon_Z}, \tag{5}$$

where $\langle q\rangle$ is the probability of nuclear capture of a pion by a proton in a $\langle p\pi^-\rangle$ atom in the presence of the interception (4), $\epsilon_Z = m/n$ is the "concentration" of the atoms Z in substance $Z_mH_n$, and $\langle\Lambda_Z\rangle$ is the interception constant for the reaction (4). This means that for a reliable separation of the "chemical" effects in nuclear capture of $\pi^-$ mesons by bound hydrogen it is necessary to be able to take quantitative account of the contribution of the interception to the suppression of the probability W. At the present time, the interception of $\pi^-$ mesons in mixtures of free hydrogen with other atoms has been sufficiently well studied—in mechanical mixtures $H_2$ + Z.[7] However, the direct utilization of the results of the experiments of[7] to take into account the interception of $\pi^-$ mesons in hydrogen-containing compound is impossible, since according to[6] the interception intensities in mixtures $H_z$ + Z and in systems $Z'_mH_n$ + Z are greatly different.

The purpose of the present study was to examine the process (4) observed in our preceding work[6] and to explain the difference between it and the process $p\pi^-$ + Z → $Z\pi^-$ + p in $H_z$ + Z mixtures. To this end we have compared the transfer of $\pi^-$ mesons to carbon in pure methane, ethane, ethylene, and in mixtures of these gases with hydrogen. Inasmuch as the bulk of the hydrogen mesic atoms in the mixtures $H_2$ + $C_mH_n$ is produced on free hydrogen,[3] it becomes possible to separate the interception channel

$$p\pi^-+\langle C\rangle_{C_mH_n}\to C\pi^-+p, \tag{6}$$

and to compare its intensity with the intensity of the process

$$\langle p\pi^-\rangle+\langle C\rangle_{C_mH_n}\to C\pi^-+p, \tag{7}$$

which takes place in chemical compounds of the type $C_mH_n$. The experiment was performed with an 80-MeV $\pi^-$-meson beam from the JINR synchrocyclotron. The organization of the experiment is analogous to that described by us earlier.[8]

## INTERCEPTION OF Π MESONS IN THE HYDROCARBON SERIES

In the series of single-type chemical compound such as saturated hydrocarbons $C_mH_n$, the character of the C—H chemical bond does not change on going from one compound to the other. Therefore the coefficients a calculated from the experimental values of W by formula (3) should have the same values for all $C_mH_n$ molecules. The presence of interception of the mesons to carbon will lead to a dependence of the constant a on the "concentration" of the carbon atoms in those molecules, and the intensity of the process (7) can be assessed from this dependence. The same is true also of the series of unsaturated hydrocarbons.

The gaseous hydrocarbons $CH_4$, $C_2H_6$, and $C_2H_4$ were frozen in hermetically sealed stainless-steel cells and placed in the beam of $\pi^-$ mesons in a styrofoam vessel filled with liquid nitrogen. The measurements with equal-size cells filled with hydrogen gas (~0.01 g/cm$^3$) and with a polyethylene target $(CH_2)_n$ were made under the same conditions.

TABLE I

| Compound $C_mH_n$ | $W$, $10^{-3}$ | $\varepsilon = \frac{m}{n}$ | $a$ |
|---|---|---|---|
| $CH_4$ | 27.80±0.60 | 0.25 | 2.50±0.05 |
| $C_2H_6$ | 21.1±0.60 | 0.33 | 2.28±0.06 |
| $C_5H_{12}$ | 15.90±0.55 [9] | 0.42 | 2.06±0.05 |
| $C_6H_{14}$ | 16.60±0.54 [9] | 0.43 | |
| $C_{12}H_{26}$ | 15.20±0.70 [9] | 0.46 | 1.98±0.06 |
| $C_{17}H_{36}$ | 14.00±0.52 [9] | 0.47 | |
| $(CH_2)_n$ | 14.50±0.40 | 0.50 | 2.07±0.05 |
| $C_6H_{12}$ | 14.30±0.55 [9] | 0.50 | |
| $C_2H_4$ | 9.87±0.30 | 0.5 | 1.42±0.04 |
| $C_6H_6$ | 3.90±0.30 [9] | 1.0 | 0.98±0.08 |
| $C_{12}H_{10}$ | 2.76±0.31 [9] | 1.2 | 0.82±0.09 |
| $C_{18}H_{14}$ | 2.76±0.31 [9] | 1.3 | 0.88±0.09 |
| $C_{10}H_8$ | 2.00±0.15 [9] | 1.25 | 0.61±0.05 |

The probabilities W for the investigated organic compounds were normalized to the yield of the reaction (2) from $H_2$. Table I lists the values of the probabilities W, the coefficients a, and the atomic concentrations of the carbon for all the compounds investigated by us.

As seen from the table, the coefficient a decreases monotonically, within the limits of the measurement errors, with increasing "concentration" of the carbon in the $C_mH_n$ molecules of both series of compounds. At the same time, on going from polyethylene and cyclohexane to ethylene, which have a different type of chemical bond at identical values of $\epsilon$, the coefficient a changes jumpwise, in analogy with the earlier observations.[1] The transition from saturated compounds to unsaturated ones consists of replacement of the $sp^3$-hybrid orbital, which effects the C—H bond, by an $sp^2$-orbital, in which the carbon is more electronegative, and it is this which decreases the probability W. After renormalization of the coefficients a for compounds of the unsaturated series, by multiplication by the coefficient $\alpha = (W_{CH_2} + W_{C_6H_{12}})/2W_{C_2H_4}$, the function $a(\epsilon)$ was approximated by the formula[7]

$$a = \frac{A}{1 + \langle \Lambda_C \rangle m/n}, \tag{8}$$

where A is the renormalized value of the coefficient a, free of the influence of the pion transfer; $\langle \Lambda_C \rangle$ is the constant for the interception of $\pi^-$ mesons by the carbon $\langle C \rangle_{C_mH_n}$. The result was

$$\langle \Lambda_C \rangle = 1.6 \pm 0.2, \; A = 3.54 \pm 0.17. \tag{9}$$

The constant $\langle \Lambda_C \rangle = 1.6 \pm 0.2$ obtained in the study of the interception in the simplest case in the $C_mH_n$ series coincides within the limits of the measurement error with the value $\langle \Lambda_C \rangle = 1.0 \pm 0.4$ obtained in the study of interception in mixtures of gases $CH_4 + Ar$, $C_2H_4 + Ar$ and liquids $C_{10}H_{22} + CCl$ and $C_6H_6 + CCl_4$.[6] According to the phenomenological model[7] the constant $\langle \Lambda_C \rangle$ is equal to the ratio of the rates of the interception (7) and of the de-excitation that leads to the capture (1) in collisions between the mesic atom and the atoms of the bound hydrogen. The fact that $\langle \Lambda_C \rangle$ is close to unity means that the rates of the interception (7) and of the de-excitation that leads to the capture (1) are equal for $\langle p\pi^- \rangle$ mesic atoms produced upon dissociation of the $Z\pi^-H$ molecule.

## INTERCEPTION OF $\Pi^-$MESONS IN GAS MIXTURES HI + CmHn

Hydrogen mesic atoms of two types are produced in the $H_2 + C_mH_n$ mixtures: $p\pi^-$ on free hydrogen and $\langle \pi p^- \rangle$ on bound hydrogen. As shown earlier[7], the interception is due to collisions of the hydrogen mesic atoms with heavy atoms. In the $H_2 + C_mH_n$ mixtures, besides the interception processes (6) and (7) considered above, it is necessary to take into account the de-excitation of the hydrogen mesic atoms in collisions both with $H_2$ molecules and with the $C_mH_n$ molecules, owing to the presence of hydrogen in the latter. In general form for the mixture $H_2 + C_mH_n$ we have

$$W(H_2 + \varepsilon X) = \left(q + \varepsilon \frac{W_x}{\langle q_x \rangle} \langle q \rangle \frac{B_x}{B_H}\right) \Big/ \left(1 + \varepsilon \frac{B_x}{B_H}\right), \tag{10}$$

where $B_H$ and $B_X$ are the stopping abilities of the hydrogen atom and of the molecule X, $\epsilon$ is the molecular concentration of the hydrogen in the mixture, $W_X/\langle q_X \rangle$ is the probability of formation of the $\langle p\pi^- \rangle$ mesic atom in the mixture, and q and $\langle q \rangle$ are the probabilities of nuclear capture in the presence of processes (6) and (7), respectively. The values of $\langle q_X \rangle = a_X/A$ for methane, ethane, and ethylene were determined from the data of Table I with the aid of formula (9) and turned out to be

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

In the representations of the phenomenological interception model[7] for the $H_2 + C_mH_n$ mixture

$$q = \frac{1 + \varkappa\varepsilon}{1 + (\Lambda + \varkappa)\varepsilon}, \quad \langle q \rangle = \frac{1 + \langle \varkappa \rangle \varepsilon}{1 + (\langle \Lambda \rangle + \langle \varkappa \rangle)\varepsilon}, \tag{11}$$

where $\Lambda$ and $\kappa$ are the constants of the interception (6) and of the de-excitation of the $p\pi^-$ atom upon its collisions with the $C_mH_n$ molecules, leading to the nuclear capture of the pion by the proton; $\langle \Lambda \rangle$ and $\langle \kappa \rangle$ are the same quantities for the $\langle p\pi^- \rangle$ mesic atom. In the experiment we determined the probabilities $W_X$ for all the organic gases $C_mH_n$ and $W(H_2 + \epsilon X)$ for different concentrations of the mixtures $H_2 + CH_4$, $H_2 + C_2H_6$, $H_2 + C_2H_4$. The results are listed in Table II, which gives the values of the constants referred to one corresponding atom of the $C_mH_n$ molecule; the constants $\langle \Lambda \rangle$ and $\langle \kappa \rangle$ are poorly determined from our data, and therefore Table II lists only their sum (for the molecule).

Within the limits of the measurement errors, the constant for the interception of the $\pi^-$ meson from the free hydrogen by the carbon of the $C_mH_n$ molecules is the same for the carbon atom contained in methane, ethane, or ethylene, $\Lambda_{\langle C \rangle} = 4.6 \pm 0.3$, and agrees with the value $\Lambda_C = 5.0 \pm 0.5$ that can be obtained by interpolation of the data on the mixtures $H_Z + Z$ (where Z : He, Ne, Ar, Kr, Xe)[10] in the same range of carbon concentrations. This means, in particular, that with respect to the $p\pi^-$ mesic atoms, the carbon atoms in the $C_mH_n$ molecules behave like free ones, and consequently the dimensions of the $p\pi^-$ mesic atoms are smaller than the dimensions of the carbon atoms.

The de-excitation constant $\kappa_{\langle p \rangle}$ for all three investigated hydrocarbons is the same according to our estimate, $\kappa_{\langle p \rangle} \sim 0.3$. This means that the bound hydrogen interacts less effectively, by an approximate factor 1/3, in the de-excitation of the $p\pi^-$ mesic atoms than the free hydrogen. The appreciable decrease of the constant for the interception by carbon ($\langle \Lambda_C \rangle = 1.6 \pm 0.2$) for the

TABLE II

| Type of $H_2 + C_mH_n$ mixture | Range of molecular concentration of hydrogen in mixture | $\Lambda_{\langle C \rangle} = \frac{\Lambda_{C_mH_n}}{m}$ | $\varkappa_{\langle p \rangle} = \frac{\varkappa_{C_mH_n}}{n}$ | $\langle \Lambda_C \rangle + \langle \varkappa \rangle$ |
|---|---|---|---|---|
| $H_2 + CH_4$ | 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 |
| Average | | 4.6±0.3 | 0.3±0.1 | |

$\langle p\pi^- \rangle$ mesic atoms produced on bound hydrogen, compared with the constant $\Lambda_C = 4.6 \pm 0.3$ for $p\pi^-$ mesic atoms, is apparently due to the weaker excitation of the $\langle p\pi^- \rangle$ mesic atoms at the instant of their production. In this case, a decrease will take place both in the transfer cross section, since the dimensions of the mesic atom are $\sim n^2$,[1] and in its lifetime (the rate of nuclear capture of the $\pi^-$ meson by a proton in the mesic atom is $\Gamma_{ns} \approx 1.1 \times 10^{15}/n^3$ [$sec^{-1}$]). The results contradict the concepts developed in[11], according to which it is assumed that $\langle p\pi^- \rangle$ mesic atoms are produced in hydrogen-containing chemical compounds with a principal quantum number $n \sim 30-70$.

It should be noted that the lower intensity of the interception of the $\pi^-$ mesons in chemical compounds $Z_mH_n$ and in mixtures $Z'_mH_n + A$ in comparison with transfer in $H_2 + Z$ mixtures cannot be connected with the contribution of the direct nuclear capture of the $\pi^-$ mesons by hydrogen from the mesic-molecular states $Z\pi^-H$.[12] Direct nuclear capture from mesic-molecular states is possible only for orbital-momentum values $l = 0$. Mesic-molecular states correspond to energy levels of a $p\pi^-$ mesic atom with principal quantum number $n \sim 14$.[12] Direct nuclear capture of pions from mesic-molecular states will be suppressed to a level $\sim 10^{-4}$ by the action of two factors: a) in the case of a statistical distribution of the pions over the orbital momentum $l$ when they are captured, the probability of finding the pion in the vicinity of a proton with $l = 0$ is $\sim 1/n^2 \leq 10^{-2}$; b) the rate $\Gamma_s \sim 4 \times 10^{11}$ $sec^{-1}$ of nuclear capture of the pion by a proton from an s-state with $n \sim 14$ is small ($\sim 10^{-2}$) in comparison with the rate $\Gamma_{H_2} \sim 10^{13}-10^{14}$ $sec^{-1}$ of the disintegration of the mesic molecule $H_2\pi^-$.[13]

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[3)]The fraction of hydrogen mesic atoms $(\pi p^-)$ produced on bound hydrogen in the $H_2 + C_mH_n$ mixture amounts under our conditions to $\lesssim 1-20\%$.


[1] S. S. Gershteĭn, V. I. Petrukhin, L. I. Ponomarev, and Yu. D. Prokoshkin, Usp. Fiz. Nauk **97**, 3 (1969) [Sov. Phys.-Usp. **12**, 1 (1969)].

[2] L. I. Ponomarev, Yad. Fiz. **2**, 223 (1965); **6**, 389 (1967) [Sov. J. Nucl. Phys. **2**, 160 (1966); **6**, 281 (1968)].

[3] Z. V. Krumshteĭn, V. I. Petrukhin, L. M. Smirnova, V. M. Suvorov, and I. A. Yutlandov, Preprint JINR R12-5224, Dubna, 1970.

[4] L. Vil'gel'mova, P. Zimrot, V. I. Petrukhin, V. E. Risin, L. M. Smirnova, V. M. Suvorov, and I. A. Yutlandov, Zh. Teor. Eksp. Fiz. **65**, 24 (1973) [Sov. Phys.-JETP **38**, 12 (1974)].

[5] V. I. Gol'danskiĭ, N. N. Zatsepina, V. I. Petrukhin, V. E. Risin, V. M. Suvorov, I. F. Tupitsin, N. I. Kholodov, and I. A. Yutlandov, Dokl. Akad. Nauk SSSR **213**, 1333 (1974).

[6] V. I. Petrukhin, V. E. Risin, and V. M. Suvorov, Yad. Fiz. **19**, 626 (1974) [Sov. J. Nucl. Phys. **19**, 317 (1974)].

[7] V. I. Petrukhin, Yu. D. Prokoshkin, and V. M. Suvorov, Zh. Eksp. Teor. Fiz. **55**, 2173 (1968) [Sov. Phys.-JETP **28**, 1151 (1969)].

[8] V. I. Petrukhin, Paper at 4th Internat. Conf. on High-Energy Physics and Nuclear Structure, Sept. 2—11, 1971, Dubna, 1972.

[9] Z. V. Krumshteĭn, V. I. Petrukhin, V. E. Risin, L. M. Smirnova, V. M. Suvorov, and I. A. Yutlandov, Zh. Eksp. Teor. Fiz. **65**, 455 (1973) [Sov. Phys.-JETP **38**, 222 (1974)].

[10] V. I. Petrukhin and V. M. Suvorov, Abstracts of Papers at 4th Internat. Conf. on High-Energy Physics and Nuclear Structure, Sept. 2—11, 1971, Dubna, 1972.

[11] N. I. Kholodov and V. I. Gol'danskiĭ, Khim. Vys. Énerg. **8**, 180 (1974).

[12] L. I. Ponomarev, Ann. Rev. Nucl. Sci. **23**, 395 (1973).

[13] A. S. Wightman, Thesis, Princeton Univ., 1949 (unpubl.); Phys. Rev. **77**, 521 (1950).



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