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PROCESSES INVOLVED IN PION CAPTURE IN HYDROGEN-CONTAINING MOLECULES

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Abstract

A systematic analysis is presented of the possible elementary processes determining the fate of negative pions stopped in hydrogen-containing samples. Using a phenomenological description in comparison with the available experimental information on pion capture in hydrogen, it is shown that the formation and decay of $p\pi^-$ atoms in compounds Z_mH_n are determined mainly by the processes of Auger capture in a molecular orbit $ZH\pi^-$, transition from molecular to atomic orbit, transfer of pions to atoms Z in collisions $p\pi^-+Z$, and nuclear capture in collisions $p\pi^-+H$. The recent assumption of a considerable role of the processes of radiative atomic capture in bound hydrogen atoms, nuclear capture of pions by protons from the molecular state $ZH\pi^-$, or "inner" transfer of the pion via tunnelling through the bond Z-H is not supported by the theory and contradicts the experimental data.

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Pion capture by bound hydrogen has proved to be a unique information source on the electronic state of hydrogen in various substances. The W probability, that a negative pion stopped in a sample with bound hydrogen will be absorbed by a proton, is closely related to the properties of the chemical bond of hydrogen [1,2]. The method used in the pionic hydrogen experiments is described in refs. [1-4], the results are summarized in reviews [1-3]. The experimental data have been analysed using the model of large mesic molecules proposed by L.I. Ponomarev [1,2].

In order to clarify the roles of the various elementary processes, considered at that time to be possibly involved in the formation and decay of pionic hydrogen atoms in condensed substances, V.I. Petrukhin et al. carried out a systematic experimental investigation of pion capture by protons in gas mixtures H_2+Z [5,6], C_mH_n+Z [7,8] and ^{3}He+Z [9]. The results confirmed the model of large mesic molecules and led to the conclusion that the formation and the decay of pionic hydrogen atoms are determined by collisional processes.

Recently, D.F. Jackson et al. [10,11] have attributed a considerable role in pion capture by hydrogen to elementary processes, not considered earlier: (i) the direct formation of pionic hydrogen via radiative atomic capture of pions in bound hydrogen atoms (thereby avoiding the molecular state); (ii) the direct nuclear capture of the pion by the proton from the molecular state $ZH\pi^-$ without forming a $p\pi^-$ atom; and (iii) an "inner" transfer of the pion from the $p\pi^-$ atom to atom Z via tunnelling through the bond Z-H.

The recent theoretical picture of the atomic capture of mesons does not support processes (i)-(iii). In the involved energy region of the mesons the cross section of the Auger-capture highly overrates that of the radiative capture [2,12-15]. The radiative nuclear capture by a proton is considered to have a small probability even in an isolated $p\pi^-$ system [2,3], and the pion is assumed to transit from molecular to atomic state very fast [2,16]. As to the "inner" transfer, the $p\pi^-$ system is neutral and relatively small, and it is supposed to leave the molecule with a high kinetic energy after its formation [2].

The fact that the assumption on a considerable role of processes (i)-(iii) is in controversion with the recent theoretical models makes it very important to investigate their consistency with the available experimental information. The aim of this paper is to undertake a systematic analysis of the experimental data using all possible elementary processes including (i)-(iii) within the frame of the same model used in refs. [10,11].

The phenomenological model generally used for the analysis of the experimental data [1-11] describes the pion capture by a proton in the consecutive steps of Coulomb capture of the pion in a mesic molecular orbit by probability P, the transition from molecular to $p\pi^-$ atomic state by probability Q, and finally, the nuclear capture of the pion by a proton with probability R. Thus the probability that a stopped pion will be absorbed by a proton is [2]

$$W = PQR \; . \qquad (1)$$

In a general case, including the processes (i)-(iii) eq. (1) should be modified to

$$W = [PQ+D]R + PE \; , \qquad (2)$$

where E is the probability of process (ii), the nuclear capture of the pion by the proton from the molecular orbit, and D is the probability of process (i), the radiative transition of the pion from the continuum to a

$p\pi^-$ atomic bound state, i.e. that of the radiative atomic capture of the pion in a hydrogen atom (see fig. 1).

In the following the rates of the collisional processes are assumed to be proportional to the concentrations of the species involved. This assumption has a firm theoretical [13,14,17] and experimental [9] support. The atomic probabilities depend on the properties of the corresponding atoms; we shall assume a dependence on atomic number Z without attempting a detailed description. By definition, $W(H_2) = 1$.

In a Z_mH_n compound, probabilities P and D can be expressed using the α_m, α_r and α_Z cross sections of pion capture in the $ZH\pi^-$, $p\pi^-$ and $Z\pi^-$ states and the N_H and N_Z densities of H and Z atoms in the sample:

$$P = \frac{\alpha_m N_H}{(\alpha_m+\alpha_r)N_H + \alpha_Z N_Z} = \frac{A_m}{1 + A_Z C_Z} \tag{3}$$

and

$$D = \frac{\alpha_r N_H}{(\alpha_m+\alpha_r)N_H + \alpha_Z N_Z} = \frac{A_r}{1 + A_Z C_Z}, \tag{4}$$

where $A_m = \frac{\alpha_m}{\alpha_m+\alpha_r}$, $A_r = \frac{\alpha_r}{\alpha_m+\alpha_r}$, $A_Z = \frac{\alpha_Z}{\alpha_m+\alpha_r}$ are the cross sections relative to $(\alpha_m+\alpha_r)$ and $C_Z = N_Z/N_H = m/n$ is the atomic concentration of Z in the sample.

The E probability of nuclear capture from $ZH\pi^-$ in a proton and the Q transition probability are independent from the C_Z concentration but may depend on Z due to the Z-H chemical bond.

The R probability of nuclear capture by proton from a $p\pi^-$ atom can be expressed in terms of the cross sections β_x of the following competing reactions:

- pion capture in proton via radiative process within the $p\pi^-$ atom (β_r);

- pion capture in a proton in collisions of $p\pi^-$ with hydrogen (β_H) or with Z (β_Z);
- pion transfer from $p\pi^-$ to Z via tunnelling through bond Z-H (λ_t);
- pion transfer in collisions $p\pi^-$ + Z (λ_Z):

$$R = \frac{\beta_H N_H + \beta_Z N_Z + \beta_r}{\beta_H N_H + \beta_Z N_Z + \beta_r + \lambda_t + \lambda_Z N_Z} = \frac{\beta_H + \beta_Z C_Z + \beta_r/N_H}{\beta_H + (\beta_Z+\lambda_Z)C_Z + (\beta_r+\lambda_t)/N_H} . \quad (5)$$

There is extensive experimental evidence that the W probability of pion capture in protons does not depend on the N_H density of hydrogen but depends sensitively on the C_Z concentration of the other constituent [1-3]. For example, the W probability measured in HD and H_2+D_2 [18] or in C_2H_6 [19] gases did not change within the experimental error when the density was increased by two orders of magnitude. Thus, the cross section of both the radiative nuclear capture in the $p\pi^-$ atom (β_r) and the "inner" transfer of pions (λ_t) must be negligibly small as compared to the other cross sections in (5). Neglecting β_r and λ_t and using relative cross sections $B_Z = \beta_Z/\beta_H$ and $\Lambda_Z = \lambda_Z/\beta_H$, eq. (5) can be written as

$$R = \frac{1 + B_Z C_Z}{1 + (B_Z+\Lambda_Z)C_Z} . \quad (6)$$

The study of pion capture by ^3He in mixtures of ^3He with noble gases [9] is the simplest possible check of our model as in that case we have neither transfer ($\lambda_Z = 0$, i.e. $R = 1$), nor chemical bond effects ($Q = 1$, $E = 0$). Thus, from (2)-(4)

$$W(^3He+Z) = P+D = \frac{1}{1 + A_Z C_Z} \quad (7)$$

in agreement with the experimental data [9]. (In (7) P denotes the probability of Auger-capture of π^- in ^3He.)

In the mixtures of H_2 with noble gases [5,6] there is no chemical bond between Z and H, i.e. E+Q = 1. Using eqs. (2)-(6), the probability of pion capture in protons is

$$W(H_2+Z) = \frac{1}{1 + A_Z C_Z} \left[(1 - A_m E) \frac{1 + B_Z C_Z}{1 + (B_Z + \Lambda_Z) C_Z} + A_m E \right] . \tag{8}$$

The experimental $W(H_2+Z)$ values measured for all noble gases Z in a wide concentration range $0 < C_Z < 2$ have been fitted with a satisfactory agreement by the simple function [6]

$$W_{exp}(H_2+Z) = \frac{1}{1 + \bar{A}_Z C_Z} \cdot \frac{1}{1 + \bar{\Lambda}_Z C_Z} , \tag{9}$$

where the $\bar{A}_Z$ and $\bar{\Lambda}_Z$ parameters have been found to be proportional to $(Z^{1/3} - 1)$:

$$\bar{A}_Z = (7.1 \pm 0.1)(Z^{1/3} - 1) \tag{10a}$$

$$\bar{\Lambda}_Z = \bar{A}_Z C_Z^{1/3} . \tag{10b}$$

$\bar{A}_Z$ in (9) is obviously an estimation of A_Z in (8). As to the square brackets in (8), its reciprocal value can be transformed to the form

$$\left[\ldots\ldots \right]^{-1} = \frac{1 + (B_Z + \Lambda_Z) C_Z}{1 + (B_Z + A_m E \Lambda_Z) C_Z} . \tag{11}$$

This expression cannot have the quasilinear $(1 + \bar{\Lambda}_Z C_Z)$ form in the region $0 < C_Z < 2$ required by (9) unless both B_Z and $A_m E$ are negligibly small. We conclude that in H_2+Z mixtures in the collisions $p\pi^-$+Z the transfer process dominates over the pion capture in proton, and no pion capture is observed from the $H_2\pi^-$ molecular state. The first statement implies $B_Z = 0$, the second one $A_m = 0$ or $E = 0$. Whichever is small of A_m and E, it should be small in other hydrogen-containing chemical systems as well because they are related mainly to the hydrogen atom itself. However, strong chemical effects have been observed in the W pion capture probability in various substances [1-4], e.g.

$$\frac{W(N_2+2H_2)}{W(N_2H_4)} = 30 \ , \qquad (12)$$

which suggests $A_m >> A_r$ as the cross section of radiative atomic capture in hydrogen should not depend on the properties of the Z-H bond. Thus, E = 0, the probability of nuclear capture of the pion by the proton from the molecular orbit is negligible.

The experimental data obtained on the mixtures of methane (ethane, ethylene) with noble gases [8] gives support to all considerations made by us earlier, as the observed effect of the noble gas added to C_mH_n could be approximated as

$$\frac{W_{exp}(C_mH_n+Z)}{W_{exp}(C_mH_n)} = \frac{1 + \overline{A}_C(m/n)}{1 + \overline{A}_C(m/n) + \overline{A}_Z c_Z} \times \frac{1 + \overline{\Lambda}_C(m/n)}{1 + \overline{\Lambda}_C(m/n) + \overline{\Lambda}_Z c_Z} \qquad (13)$$

using (10a) for $\overline{A}_C$ and $\overline{A}_Z$ and an estimation from earlier data for $\overline{\Lambda}_C$, with only $\overline{\Lambda}_Z$ as a parameter.

Thus, we have shown that the assumption of a considerable role of processes (i)-(iii), used for the interpretation of data on pion capture by a proton in organic molecules [10,11], is inconsistent with the available experimental information. The smallness of the corresponding probabilities is in agreement with the recent theoretical picture of the atomic capture of mesons.

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Figure caption

1. The fate of a slow π^--meson in a compound Z_mH_n. The pion is captured in a molecular state $ZH\pi^-$ or in atomic orbits of $p\pi^-$ and $Z\pi^-$ with probabilities D, P and (1-P-D), respectively. The pionic molecule may decay via pion capture in a proton or by pion transition to atomic orbits $p\pi^-$ and $Z\pi^-$. The pion can be transferred from $p\pi^-$ to Z, or absorbed by a proton.

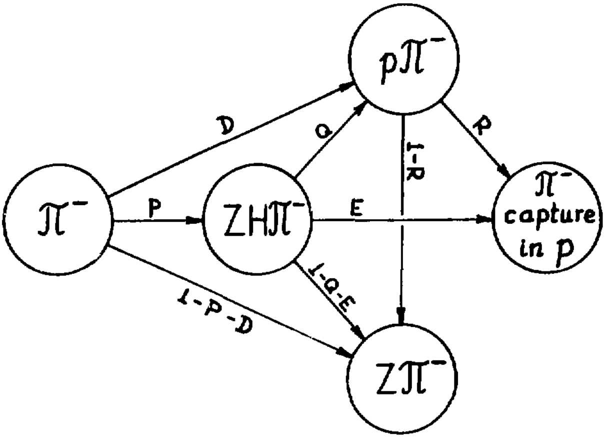

Fig. 1