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TRANSFER OF π⁻ MESONS IN A HYDROGEN-DEUTERIUM GAS MIXTURE

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The transfer of negative pions from hydrogen to deuterium in an $H_2 + D_2$ gas mixture is investigated. The observed singularities of the transfer can be explained within the framework of the phenomenological model.

1. INTRODUCTION

IN our earlier paper[1] it was shown that negative pions stopped in a mixture of hydrogen with heavier gases having a charge Z are intensely captured from the hydrogen by the Z atoms. The results can be described within the framework of the phenomenological model[1,2] according to which: 1) the π^- mesons are decelerated in the $H_2 + Z$ mixture and are captured at higher levels of the mesic molecules or mesic atoms of H_2 and Z with a probability proportional to the charges of the nuclei H_2 and Z; the π^- meson captured by hydrogen at the mesic-molecule levels drops to the level of the isolated $p\pi^-$ mesic atom; 2) as a result of collisions of the excited $p\pi^-$ mesic atom with the hydrogen nuclei and the impurity Z, the π^- meson is captured by the proton or is transferred by the Z atom.

The rate of nuclear capture of the π^- meson by the proton in the $p\pi^-$ mesic atom (ω_H) and of the transfer of the π^- meson from the $p\pi^-$ mesic atom to the Z nuclei (ω_Z) are proportional to the collision frequency, i.e., to the densities (numbers of atoms per cm^3) ρ_H and ρ_Z of the hydrogen and of the gas Z[2]:

$$\omega_H = a\rho_H + b\rho_Z, \quad (1)$$

$$\omega_Z = g\rho_Z. \quad (2)$$

Here $g = g_{pZ} - g_{Zp}$; g_{pZ} and g_{Zp} are the constants for the transfer of the negative pions from H to z and from Z to H. When $Z > 1$, the coefficient $g_{Zp} = 0$, since the $Z\pi^-$ mesic atom is electrically charged and cannot come sufficiently close to the proton.

In the employed notation, the probability Q of the transfer of the π^- mesons from the hydrogen to the Z atoms is

$$Q = \frac{\Lambda C}{1 + (\Lambda + \varkappa)C}, \quad (3)$$

where $C = \rho_Z/\rho_H$ is the relative atomic concentration of the impurity Z, $\Lambda = g/a$, and $\kappa = b/a$.

In accordance with the experimental data[1], the transfer probability (3) depends not on the density of the individual gases of the mixture, but only on the relative concentration C. For the investigated gaseous mixtures of hydrogen with helium, nitrogen, neon, and argon[1], the transfer capture is linear in Z:

$$\Lambda = (0.7 \pm 0.2)Z. \quad (4)$$

The values of κ turned out to be small,

$$\varkappa \ll \Lambda, \quad (5)$$

and the probability of transfer Q is close to unity in the region of large concentrations C.

Among the $H_2 + Z$ mixtures, a special position is occupied by the mixture of hydrogen with deuterium. Since the $d\pi^-$ mesic atom is electrically neutral, there should occur in the $H_2 + D_2$ system, together with the transfer of the π^- mesons from hydrogen to deuterium, also an intense inverse transfer from the deuterium to the hydrogen:

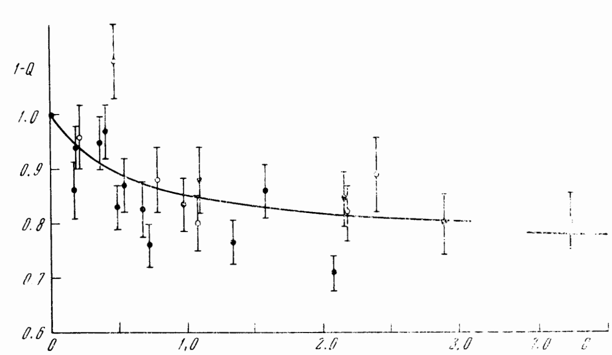
$$p\pi^- + d \rightleftarrows d\pi^- + p, \quad (6)$$

i.e., the coefficient $g_{Zp}(g_{dp})$ in (2) does not vanish, as in the case of mixtures of hydrogen with other elements, but $g_{dp} \approx g_{pd}$ and $\Lambda \ll \kappa$. In addition, for the $H_2 + D_2$ mixture we should expect $a \approx b$, i.e., $\kappa \approx 1$, unlike in $H_2 + Z$ mixtures with $Z > 1$. In the case of the $H_2 + D_2$ mixture, relation (5) should be reversed, and $Q \ll 1$. Therefore, an increased measurement accuracy is necessary to investigate transfer in the $H_2 + D_2$ system.

The purpose of the present investigation was to observe experimentally the transfer of π^- mesons in an $H_2 + D_2$ gas mixture and to study the characteristics of this process. Preliminary results were reported at the January 1964 session of the Nuclear Physics Division of the USSR Academy of Sciences.

2. MEASUREMENT RESULTS

The experiments were performed with the synchrocyclotron of the Nuclear Problems Laboratory of JINR,



Dependence of the probability Q of the transfer of π^- mesons from hydrogen to deuterium on the relative deuterium concentration C. The hydrogen density in units of $10^{-3}\rho_H^0$ is equal to 12 (light circles) and 27 (filled circles) (under normal conditions the density of gaseous hydrogen is $1.3 \times 10^{-3}\rho_H^0$). Curve–the relation (3) calculated for $\Lambda = 0.4$ and $\chi = 1.3$ [7].

using a procedure described earlier[1,3]. The transfer probability Q was determined by measuring the yields of the gamma quanta from the charge exchange of the π^- mesons captured by the hydrogen nuclei:

$$\pi^- + p \rightarrow \pi^0 + n, \quad \pi^0 \rightarrow 2\gamma \tag{7}$$

(the charge exchange of the stopped π^- mesons in deuterium, $\pi^- + d \rightarrow \pi^0 + 2n$, is suppressed by a factor of more than 10^3 [4,5]). In the course of the measurements, we varied the relative concentration $C = \rho_H/\rho_H$ at a fixed hydrogen density ρ_H.

The obtained dependence of Q on C is shown in the figure. We see that a transfer of π^- mesons from hydrogen to deuterium is observed in $H_2 + D_2$ gas mixture. When the relative concentration C increase, the transfer has a tendency to saturate. Control experiments in which the target was cooled to the temperature of liquid nitrogen, have shown that Q is independent of the mixture temperature.

3. DISCUSSION

The measurements of the Q(C) dependence were performed at two values of the hydrogen density ρ_H. As seen from the figure, the values of Q at a fixed relative concentration C are independent of ρ_H, within the limits of measurement errors, in agreement with (3).

The values of Λ and κ for the $H_2 + D_2$ mixture were determined by least squares from the data shown in the figure and turned out to be

$$\Lambda = 0.4 \pm 0.1, \quad \varkappa = 1.3 \pm 0.4. \tag{8}$$

The obtained value of Λ is smaller than the value that follows from (4), according to which $g_{pd} = (0.7 \pm 0.2)a$. From a comparison of this quantity with Λ (8) it follows that $g_{dp} = 0.3 \pm 0.2$, i.e., the intensities of the direct and inverse transfers in the $H_2 + D_2$ system are approximately equal. The close values of g_{pd} and g_{dp} are attributed to the fact that the rates of the nuclear capture of the π^- mesons by the proton and by the deuteron are approximately the same, and the isotopic difference of the levels of the excited $p\pi^-$ and $d\pi^-$ of the mesic atoms is small.

In the case of the $H_2 + D_2$ mixture, the reduced transfer constant, defined as $\Lambda_D = \Lambda\rho_H^0 a$ (where $\rho_H^0 = 4.2 \times 10^{22}$ atoms/cm^3 is the density of the liquid hydrogen and $a = (4 \pm 1) \times 10^{11}$ sec^{-1} [6]) is

$$\Lambda_D = (1.6 \pm 0.6) \cdot 10^{11}\ \text{sec}^{-1}. \tag{9}$$

The transfer constant Λ_D of the π^- mesons exceeds by one order of magnitude the analogous transfer constant λ_{pd} of the μ^- mesons in the $H_2 + D_2$ mixture, measured in experiments with small ρ_Z and equal to 10^{10} sec^{-1} [7]. In comparing Λ_D and λ_{pd} it is necessary to take into account the fact that at small deuterium concentrations the transfer of the π^- mesons proceeds only from the hydrogen to the deuterium ($g_{dp} = 0$, since the $d\mu^-$ mesic atom is in the ground state, which is lower than the ground state of the $p\mu^-$ mesic atom), whereas the rate of the direct and inverse transfers of the π^- mesons (6) are approximately the same, i.e., $\Lambda_{pd} \approx \Lambda_{dp}$, where $\Lambda_D = \Lambda_{pd} - \Lambda_{dp}$ and $\Lambda_{pd} > \Lambda_D$. The large difference between the reduced transfer constants of the π^- and μ^- mesons ($\Lambda_{pd} \gtrsim 10\,\lambda_{pd}$) is due to the effect that at small deuterium concentrations the μ^- meson transfer is from the ground state of the $p\mu^-$ meson, whereas the π^- mesons are transferred from higher orbits ($n > 1$) at $C \sim 1$. Since the transfer rate is proportional to the square of the radius of the mesic atom at small values of n ($\sim n^4$)[2], it follows from the relation between Λ_{pd} and λ_{pd} that $n \gtrsim 3$, in agreement with the estimate in[2].

The value of κ for the $H_2 + D_2$ mixture was found to be close to unity, i.e., the probabilities of the capture of the π^- meson by the proton in the $p\pi^-$ mesic atom upon collision between the mesic atom and hydrogen and deuterium atoms are practically the same. This is a natural consequence of the fact that the electromagnetic properties of the H and D atoms are quite close.

In the $H_2 + D_2$ mixture, unlike the mixtures of hydrogen with other elements, we have

$$\varkappa > \Lambda. \tag{10}$$

This means that when the $p\pi^-$ mesic atom collides with the deuterium atom, the nuclear capture of the π^- meson by the proton in the π^- mesic atom is more probable than the transfer of the π^- meson to the deuteron.

According to formula (3), in the region of large relative concentrations C, the transfer becomes saturated:

$$Q \rightarrow Q_{max} = \frac{\Lambda}{\Lambda + \varkappa}, \quad C \rightarrow \infty. \tag{11}$$

For the $H_2 + D_2$ mixture

$$Q_{max} = 0.23 \pm 0.04, \tag{12}$$

whereas for the mixtures of hydrogen with other elements[1] $Q_{max} > 0.9$.

In conclusion, we take the opportunity to thank S. S. Gershteĭn and L. I. Ponomarev for useful discussions.

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