TRANSFER OF π^- MESONS IN A MIXTURE OF HYDROGEN WITH OTHER GASES

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The transfer of π^- mesons from hydrogen to heavier elements Z has been investigated in a gaseous mixture H_2 + Z. The transfer probability is proportional to the nuclear charge Z and depends only on the relative concentration of the atoms Z. The observed features of the transfer can be explained in terms of a phenomenological model.

1. INTRODUCTION

THE process of slowing down and capture of π^- mesons in hydrogen occurs in several stages, the principal ones being as follows: 1) slowing down of the π^- mesons and their transfer from the continuous spectrum to a discrete spectrum (formation of a highly excited mesic atom or mesic molecule), 2) transfer of the mesons to low orbits, and 3) nuclear capture of the π^- mesons in an s state:

$$\pi^- + p \to \pi^0 + n, \qquad \pi^0 \to 2\gamma \tag{1}$$

and

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

For an isolated $p\pi^-$ mesic atom the capture time τ_C is determined by comparatively slow radiative transitions from the high orbits of the mesic atom to the ground state and amounts to $\sim 10^{-9}$ sec. In a real situation when the π^- mesons stop in gaseous or liquid hydrogen, the $p\pi^-$ mesic atoms formed cannot any longer be considered isolated, since the average time until they collide with other atoms is considerably smaller than τ_C. Being electrically neutral and having small dimensions, mesic atoms of hydrogen interact efficiently with other atoms, since they penetrate freely into the electron shells of other atoms and can closely approach their nuclei. The processes of $p\pi^-$ mesic-atom de-excitation and π^--meson capture occurring in such collisions (Auger effect on electrons of a neighboring atom[1] and nuclear capture from high ns states—the mechanism of Day, Snow, and Sucher[2]) are considerably more intense than the radiative transitions in an isolated $p\pi^-$ mesic atom[1] and play a determining role in the general picture of π^--meson capture in hydrogen.

For the case of π^--meson stopping in a mixture of hydrogen with heavier atoms Z, an additional process is possible—transfer of the π^- meson from a mesic atom of hydrogen to a nucleus Z in collisions¹⁾:

$$p\pi^- + Z \to Z\pi^- + p. \tag{3}$$

This process is irreversible (since the $Z\pi^-$ mesic atom is electrically charged) and leads to capture of the π^- meson by the nucleus Z.²⁾

Transfer of mesons from mesic hydrogen atoms to heavier nuclei has been observed only for μ^- mesons.[12-18] Since the lifetime of the μ^- meson in a $p\mu^-$ mesic atom considerably exceeds the duration of all the cascade transitions, then for small concentrations of the impurity Z the μ^- meson succeeds in reaching the K orbit and, remaining in it for some time (the μ^- meson interacts only weakly with the proton), is efficiently transferred in collisions of the $p\mu^-$ mesic atom with nuclei Z even for very small concentrations of the nuclei Z ($\lesssim 10^{-3}$). The rate of this transfer w_Z is proportional to the density (number of atoms per cm³) ρ_Z of the gas Z:

$$w_Z = \lambda_Z \rho_Z / \rho_H^0 \tag{4}$$

(where $\rho_H^0 = 4.2 \times 10^{22}$ atoms/cm³ is the density of liquid hydrogen), and the reduced transfer constant λ_Z is proportional to Z[14,17]:

$$\lambda_Z \approx 8 \cdot 10^9 Z \text{ sec}^{-1}. \tag{5}$$

A different situation occurs in transfer of π^- mesons. Since the rate of nuclear capture (1) and (2) from the lower states of a $p\pi^-$ mesic atom is extremely high, transfer of a π^- meson to a nucleus Z (3) is possible only from the high levels of the $p\pi^-$ mesic atom and can occur intensely only at large concentrations of the impurity nuclei Z. We can expect that the probability of such transfer, as in the case of μ^- mesons, increases with increasing Z.

The studies made previously of π^--meson capture in mixtures of hydrogen with other elements did not permit any conclusion to be drawn as to the occurrence of π^--meson capture.[15,19,20] The purpose of the present work was to observe experimentally the transfer of π^- mesons from hydrogen to heavier gases (Z > 1) and to study the characteristics of this process. Preliminary results have been reported at the January session of the Nuclear Physics Division, U.S.S.R. Academy of Sciences, in 1964.

2. EXPERIMENTAL PROCEDURE

The experiments were performed in the synchrocyclotron of the Laboratory of Nuclear Problems, Joint

¹⁾If the system H_2 + Z is not a mixture but a chemical compound, then another considerably more important mechanism is active in redistribution of the π^- mesons.[3-7]

²⁾Capture of the π^- meson by the nucleus Z leads to breakup of the nucleus, and not to charge exchange (1), which is suppressed to a level $<10^{-3} - 10^{-4}$ for all nuclei except H and He³.[8-11]

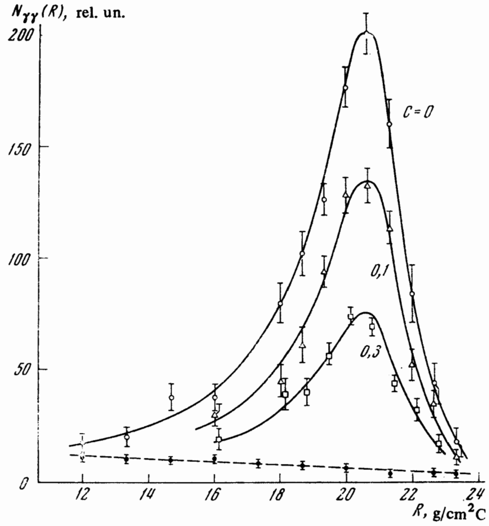

FIG. 1. Results of one of the measurements of $N_{\gamma\gamma}(R)$ for a mixture $H_2 + N_2$ (hollow points). The solid curves are $N_{\gamma\gamma}(R)$ calculated from Eq. (7) for various values of relative concentration C of nitrogen, indicated by the numbers on the curves. The solid points and the dashed line represent the contribution of charge exchange in flight $N_{\gamma\gamma}'(R)$. The hydrogen density is $\rho_H = 97 \times 10^{-3}$ ρ_H^0 (under normal conditions the density of gaseous hydrogen is 1.3×10^{-3} ρ_H^0).

Institute for Nuclear Research, by the technique described previously.[4,5,21,22] The π^- mesons with an initial energy of 80 MeV were slowed down by passage through an absorber and a series of scintillation counters and stopped in a high-pressure gas target. The target was a spherical steel vessel of volume 900 cm^3, filled with a mixture of hydrogen and other gases Z at a pressure up to 150 atm. The capture of stopped π^- mesons by hydrogen was identified by the charge-exchange reaction (1). The pairs of γ rays produced in reaction (1) were detected by means of total-absorption Cerenkov spectrometers.

The target was filled with hydrogen, to which was then added under excess pressure various amounts of the gas Z, i.e., the relative concentration C of the gas Z was changed for a fixed density of hydrogen. The amount of hydrogen in the target was determined by weighing. Measurements were made for a number of values of hydrogen density in the target ρ_H. For each mixture of gases we obtained the counting rate of γ-ray pairs $N_{\gamma\gamma}$ as a function of the thickness of the stopping absorber R. The results of one of these series of measurements are shown in Fig. 1.

In addition to process (1), the curve $N_{\gamma\gamma}(R)$ receives a small contribution also from π^--meson charge exchange in flight in the material of the target walls (the yield of γ rays from charge exchange of π^- mesons in flight in the gas filling the target is two orders of magnitude smaller). The contribution of π^--meson charge exchange in flight was determined by measuring the γ-ray pair counting rate $N_{\gamma\gamma}'$ as a function of R for an empty target (see Fig. 1). The γ-ray pair counting rate from reaction (1) $N_{\gamma\gamma}^*(R)$ was determined as the difference $N_{\gamma\gamma}(R) - N_{\gamma\gamma}'(R)$.

3. EXPERIMENTAL RESULTS

The dependence of the number of π^--meson stoppings in the gas target N_π on the absorber thickness R is related to the π^--meson range distribution F(R) by the equation

$$N_\pi(R) = \int_R^{R+\Delta} F(R')\,dR'. \tag{6}$$

Here $\Delta = \Delta_0(1 + qC)$ is the stopping thickness of the gas mixture H_2 + Z, $C = \rho_Z/\rho_H$ is the ratio of densities of the gas Z and hydrogen, $q = q_Z/q_H$ is the ratio of stopping powers of the gases, reduced to a single atom ($q \approx Z$). The initial stopping of π^- mesons in atoms of H and Z is proportional to q_H and q_Z.[23] Hence it follows that in the case when there is no transfer of π^- mesons,

$$N_{\gamma\gamma}^*(R) \sim N_\pi(R) \,/\, (1 + qC). \tag{7}$$

Introducing the probability Q of transfer of π^- mesons from hydrogen atoms to the atoms Z and the quantity

$$Y_{\gamma\gamma} = \int N_{\gamma\gamma}^*(R)\,dR, \tag{8}$$

we find that in our experimental setup (ρ_H = const, i.e., Δ_0 = const)

$$Q = 1 - Y_{\gamma\gamma}(\rho_H, C) \,/\, Y_{\gamma\gamma}(\rho_H, 0). \tag{9}$$

The π^--meson range distribution F(R) was determined by measuring the function $N_{\gamma\gamma}^*(R)$ with the target filled with hydrogen. In this case $N_{\gamma\gamma}^*(R)$ is practically identical in shape with F(R), since the width of the F(R) distribution is two orders of magnitude greater than the stopping thickness of the hydrogen target Δ_0. The transfer probability Q was found by the method of least squares by comparison of the measured and computed dependences (7)–(9).

In order to check the accuracy of the method described for determining $Y_{\gamma\gamma}$ and Q, we carried out control experiments with a hydrogen target and with targets of lithium hydride LiH, in which the stopping thickness of the targets was varied over wide limits. The values of $Y_{\gamma\gamma}$ measured in these experiments agreed with the calculated values within a few per cent.

Another means[23] was also used to determine Q. For small target stopping thicknesses

$$N_{\gamma\gamma}^*(R) \sim (1 - Q)\Delta_0 N_\pi(R + \Delta/2),$$

as follows from (6) and (7). Designating the maximum value of $N_{\gamma\gamma}^*(R)$ by $N_{\gamma\gamma\,\max}^*$ we obtain

$$Q = 1 - N_{\gamma\gamma}^*(\rho_H, C)_{max} \,/\, N_{\gamma\gamma}^*(\rho_H, 0)_{max} \tag{10}$$

to the order of the small correction $1 + q(\Delta_0)(1 + qC)$, which takes into account the finite value of the ratio of the gas target stopping thickness to the spread in π^--meson range. The method of determination described gave the same results as Eq. (9).

Figure 2 shows the Q values obtained for the gas mixtures studied of He, N_2, Ne, and Ar with hydrogen. As can be seen from this figure, transfer of π^- mesons from hydrogen to the heavier atoms is observed in all of the mixtures studied.

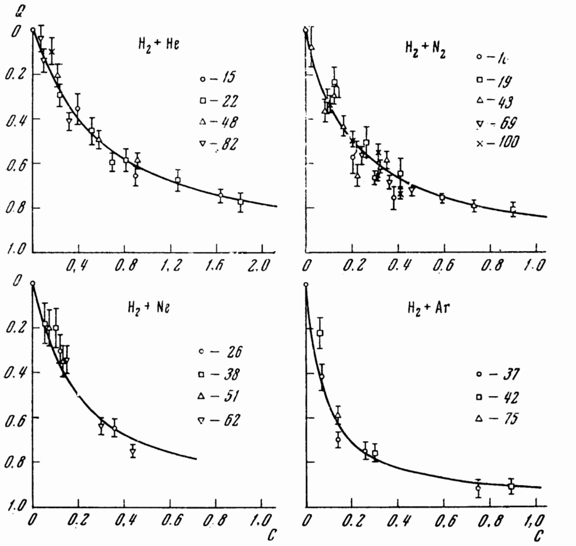

FIG. 2. Transfer probability Q for various relative concentrations C for mixtures of hydrogen with He, N_2, Ne, and Ar. The hydrogen densities in units of $10^{-3}\rho_H{}^0$ are indicated by the numbers. The curves represent Eq. (13) calculated for the Λ values listed in the table (see below), and $\kappa = 0$.

4. DISCUSSION

Measurements of Q as a function of C were made for various hydrogen densities ρ_H. As can be seen from Fig. 3, the values of Q for a fixed value of C do not depend on ρ_H within the experimental error; the intensity of transfer is determined only by the relative concentration C of the heavy atoms. Another characteristic feature of the observed transfer process is the rise in transfer probability with increasing nuclear charge of the heavy atom Z (Fig. 2).

We will discuss the experimental results obtained in terms of the following simplified scheme.

1) π^- mesons are slowed down in a mixture of gases H_2 + Z and are captured into high levels of the mesic molecules and mesic atoms of hydrogen[3)] and Z with a probability proportional to the nuclear charges (more precisely, proportional to the stopping powers $2q_H$ and q_Z); the π^- meson captured in the mesic-molecule levels of hydrogen drops down to a level of the isolated $p\pi^-$ mesic atom with a principal quantum number $3 \lesssim n \lesssim 7$.[3,7]

2) As the result of collisions of the excited $p\pi^-$ mesic atom with atoms of hydrogen and of the impurity Z, the π^- meson is captured by the proton or is transferred to an atom Z.

The rate of capture of the π^- meson by the proton in a $p\pi^-$ mesic atom, W_H, is proportional to the densities ρ_H and ρ_Z of hydrogen and the gas Z:

$$W_H = a\rho_H + b\rho_Z + \alpha. \tag{11}$$

Here α is the rate of capture of the π^- meson in an isolated $p\pi^-$ mesic atom. This quantity does not depend on

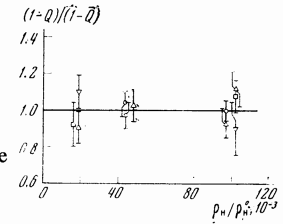

FIG. 3. Comparison of values of $(1 - Q)/1 - Q)$ for different values of ρ_H (in units of 10^{-3} $\rho_H{}^0$) and a fixed relative concentration C of nitrogen in the mixture $H_2 + N_2$: O – C = 0.09, □ – 0.20, Δ – 0.31, ∇ – 0.41 Q is the average value of Q for a given value of C.

the density of the gases, is small, and can be omitted in (11). The rate of transfer of π^- mesons from the $p\pi^-$ mesic atom to the nuclei Z, which is analogous to Eq. (4), is proportional to ρ_Z:

$$W_Z = \Lambda_Z\rho_Z / \rho_H{}^0. \tag{12}$$

With the designations adopted the transfer probability is[4)]

$$Q = \Lambda C / [1 + (\Lambda + \varkappa)C], \tag{13}$$

where

$$\Lambda = \Lambda_Z / a\rho_H{}^0, \quad \varkappa = b / a, \quad C = \rho_Z / \rho_H.$$

The phenomenological model which we have discussed predicts that the probability for transfer of π^- mesons (13) should depend not on the density of the individual gases of the mixture but only on the relative concentration C. This agrees with the experimental data (see Figs. 2 and 3). For small values of C, according to (13), Q increases linearly with increasing C:

$$Q \approx \Lambda C, \quad (\Lambda + \varkappa)C \ll 1. \tag{14}$$

In the region of high relative concentrations we should expect a fluctuation of the transfer with increasing C:

$$Q \to Q_{max} = \Lambda / (\Lambda + \varkappa), \ C \to \infty \tag{15}$$

which is reached at

$$C \gg 1 / (\Lambda + \varkappa). \tag{16}$$

The quantities Λ and κ were determined from the data of Fig. 2 by the method of least squares (see the table). The values found for Λ can be described by the linear relation (see Fig. 4):

$$\Lambda = (0.7 \pm 0.2) Z. \tag{17}$$

The reduced transfer constant Λ_Z, which is analogous to the quantity λ_Z for μ^- mesons (5), is

$$\Lambda_Z \approx 3 \cdot 10^{11} Z \ \text{sec}^{-1}, \tag{18}$$

if, following Doede et al.[24], we take $a\rho_H^0 = (4 \pm 1)$

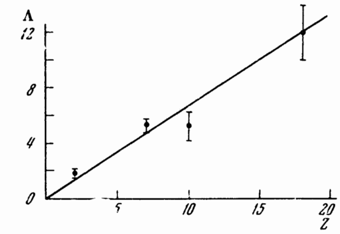

FIG. 4. Transfer constant Λ for different values of Z. The straight line is the function $\Lambda = 0.67Z$ (17).

3)The levels of the isolated $p\pi^-$ mesic atom into which the π^- meson is captured in hydrogen correspond to a principal quantum number value $n < 8$.[3,7]

4)The π^--meson decay rate is considerably less than the capture rate in the mixtures considered and can be neglected.

Gas	Z	Λ	κ	Q_{max}
He	2	1.8±0.3	<0.2	>0.90
N_2	7	5.2±0.5	<0.4	>0.93
Ne	10	5.2±1.0	<0.5	>0.91
Ar	18	12±2	<0.8	>0.94

$\times 10^{11}$ sec^{-1}, i.e., a = 1×10^{-9} cm^3/atom/sec.

The π^--meson transfer constant Λ_Z is two orders of magnitude larger than the μ^--meson transfer constant (4) and (5) determined in experiments at low impurity densities ρ_Z. This is explained by the fact that transfer of μ^- mesons for small ρ_Z occurs from the K orbit of the mesic atom, while π^- mesons for C ≈ 1 are transferred from higher orbits (n > 1). If we assume that the capture rate is proportional to the square of the radius of the mesic atom ($\sim n^4$), i.e., $\lambda_Z \approx 8 \times 10^9$ Zn^4 sec^{-1},[7] then it follows from comparison of (5) and (18) that n ≈ 3, which agrees with the estimate given in refs. 3 and 7.

For the coefficient κ we obtained values which, within the experimental errors, are consistent with zero. This indicates the absence of a noticeable influence of collisions of $p\pi^-$ mesic atoms with nuclei Z on the π^--meson capture rate by the proton. In the table we have listed the upper-limit estimates of κ at the 90% confidence level. For all gas mixtures investigated in the present work,

$$\kappa \ll \Lambda. \tag{19}$$

In the region of high relative concentrations C (16) the transfer probability is close to unity.

5. CONCLUSION

1. A characteristic feature of the π^--meson transfer studied in the present work from hydrogen to heavier atoms in a gas mixture H_2 + Z is the dependence of the transfer probability of π^- mesons only on the relative concentration of the impurity Z. This means that capture of the π^- mesons by protons is determined by collisions of $p\pi^-$ mesic atoms with hydrogen molecules, i.e., W_H is proportional to ρ_H.

2. Transfer of π^- mesons occurs intensely only at high impurity concentrations (C ≈ 1), while μ^- mesons are efficiently transferred to impurity nuclei even at very low concentrations. This is due to the great difference in the rates of the π^- and μ^- nuclear capture processes competing with the transfer.

3. Collisions of a $p\pi^-$ mesic atom with heavier atoms do not have a noticeable effect on the rate of capture of the π^- meson in a $p\pi^-$ mesic atom, which is determined mainly by collisions with hydrogen atoms. It is of interest to investigate the capture of π^- mesons in mixtures with a high concentration C, where the effect of collisions of $p\pi^-$ mesic atoms with impurity nuclei on the rate of capture of π^- mesons by protons can be observed. The transfer of π^- mesons in collision of a $p\pi^-$ mesic atom with impurity nuclei Z is considerably more probable (particularly for large Z) than capture of the π^- meson by the proton as the result of a collision of the $p\pi^-$ mesic atom with a hydrogen atom.

4. The observed features of π^--meson transfer find qualitative explanation in terms of a phenomenological model.

5. Special interest is presented by study of the transfer of π^- mesons in a gas mixture of hydrogen and deuterium. Since the $d\pi^-$ mesic atom is electrically neutral, we should expect that in a mixture $H_2 + D_2$ an intense reverse transfer of π^- mesons from deuterium to hydrogen will occur, i.e., $\Lambda \ll 1$. Furthermore, since the electromagnetic properties of the H and D atoms are similar, we expect a ≈ b and $\kappa \approx 1$, and the transfer probability for the mixture $H_2 + D_2$ should reveal saturation properties with increasing C already at C ~ 1. Finally, for this mixture $\kappa \gg \Lambda$, i.e., $Q_{max} \ll 1$. Therefore, for study of the transfer of π^- mesons from hydrogen to deuterium, increased experimental accuracy is necessary.

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