Study of atomic capture and transfer of π^- mesons in mixtures of hydrogen with other gases

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Atomic capture and transfer of π^- mesons have been studied in gaseous mixtures $H_2 + Z$, where Z represents He, Ne, Ar, Kr, Xe, N_2, and CO_2. Relative probabilities of atomic capture of pions by components of the mixtures have been measured. The relative constants Λ_Z for transfer of pions from hydrogen atoms to atoms Z have been measured. It is shown that the relative stopping powers $S_0{}^H$ of atoms Z for the pion energies at which atomic capture occurs and the transfer constants Λ_Z depend identically weakly on Z: $S_0{}^H = (7.1 \pm 0.1) \times (Z^{1/3} - 1)$ and $\Lambda_Z = S_0{}^H C^{1/3}$; the transfer constants Λ_Z are a weak function of the impurity concentration $C = n_Z/n_H$.

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Transfer of π^- mesons

$$p\pi^- + Z \to Z\pi^- + p \tag{1}$$

was observed by us in experiments on nuclear capture of π^- mesons by hydrogen in gaseous mixtures $H_2 + Z$, where Z represents He, N_2, Ne, and Ar.[1] Here it turned out that the capture rate $\lambda_Z \sim Z$, as in the case of $p\mu^-$ atoms.[2] In all other cases, however, as the result of the presence of the intense competing process of nuclear capture of the π^- meson by the proton in the mesic atom, the transfer differs strongly for π^- and μ^- mesons: 1) Transfer of π^- mesons becomes appreciable for heavy-atom atomic concentrations $C \sim 1$, while μ^- mesons are completely transferred for $C \sim 10^{-3}$–10^{-5} ($C = n_Z/n_H$, where n_Z and n_H are the numbers of atoms Z and of hydrogen per cm^3); 2) the transfer rate λ_Z^0 reduced to the density of liquid hydrogen exceeds by almost two orders of magnitude the reduced rate for μ^- mesons; 3) the transfer rate of pions to atoms of helium is comparable with the transfer rate to other atoms, whereas transfer of μ^- mesons to helium is strongly suppressed (a calculation gives $\sim 10^{-5}$)[3] and has not been observed.[4] All of these differences are due to the fact that transfer of μ^- mesons occurs from the K orbit of the hydrogen mesic atom, while π^- mesons are transferred from higher orbits.

The intense transfer of pions to He atoms is apparently due to the fact that for excited states of $p\pi^-$ atoms the hindrance mechanism discussed by Gershteĭn[5] is removed. We can therefore expect that for large concentrations of He ($C \sim 0.1$–1) in a H_2+He mixture there will be μ^--meson transfer comparable in intensity with the transfer of π^- mesons.

The present work is devoted to a detailed study of the π^--meson transfer mechanism in gaseous mixtures $H_2 + Z$, where Z represents He, Ne, Ar, Kr, Xe, N_2, and CO_2. The experiments were carried out in an 80-MeV beam of π^- mesons from the synchrocyclotron at our institute. The experimental apparatus and procedure were for the most part similar to those described by us previously.[1] The experiment measured the yield $N_{\gamma\gamma}(R, 0)$ of γ-ray pairs from decay of π^0 mesons formed in the charge-exchange reaction

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

in a gas target filled with hydrogen at a pressure of ~40 atm, and the reduction in yield $N_{\gamma\gamma}(R, C)$ as the result of transfer on addition to the hydrogen of gaseous impurities (R is the thickness of the absorber used to slow down the mesons). As an illustration we have shown in Fig. 1 the yield curves $N_{\gamma\gamma}(R, C)$ for a target with a H_2+Xe mixture for various concentrations of Xe.

After subtraction of the background due to charge exchange in flight (mainly at the target walls) and allowance for the shift in the peaks of the $N_{\gamma\gamma}(R, C)$ curves with change of concentration C, we determined the ratio α averaged over the two curves,

$$\alpha = N^*_{\gamma\gamma}(R, C)/N^*_{\gamma\gamma}(R, 0), \quad N^*_{\gamma\gamma} = N_{\gamma\gamma} - N^{\text{b.g.}}_{\gamma\gamma}.$$

The curves $N^*_{\gamma\gamma}(R, C)$ are broadened (by ~25%) and have a slow falloff at small R in comparison with the range curves. This is due to the fact that the target has the form of a sphere, so that the wall thickness in front of the mixture increases with distance from the beam axis.

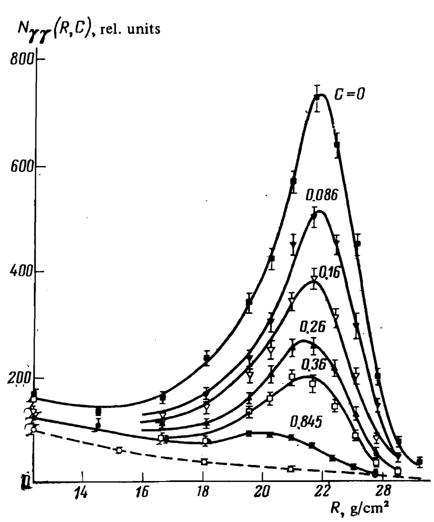

FIG. 1. Yield curves of π^0 mesons from a gas mixture H_2+Xe at various impurity concentrations C; R is the thickness of the stopping absorber. The dashed curve has been drawn through the points obtained with an empty target.

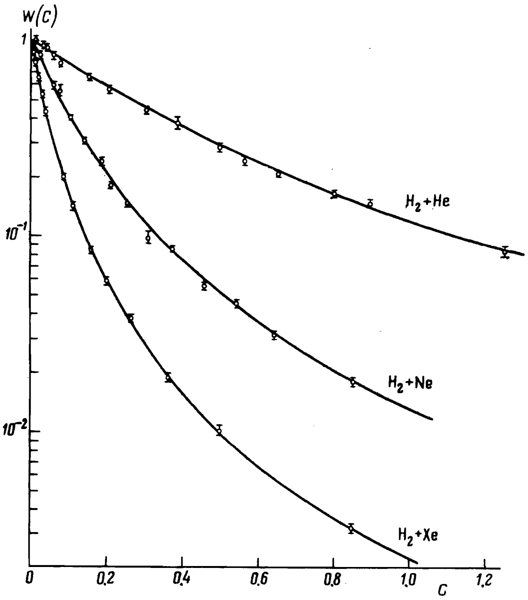

FIG. 2. Probabilities of nuclear capture of pions by hydrogen in mixtures with He, Ne, and Xe. The curves were drawn according to Eq. (5) under the conditions of (6)–(7) and with values of S_0^H from the table.

The change in shape of the curves $N^*_{\gamma\gamma}(R, C)$ with increasing impurity concentration is small, so that the curves $N^*_{\gamma\gamma}(R, 0)$ and $N^*_{\gamma\gamma}(R, C)$ are similar within the experimental errors. In this case the probability of nuclear capture by hydrogen of a π^- meson stopped in the mixture is

$$W=\frac{\alpha\Delta_H}{\Delta_{HZ}(1-\beta)}=P_H q, \qquad (3)$$

where Δ_H and Δ_{HZ} are absorbing thicknesses of hydrogen and of the mixture in the target; the coefficient β takes into account the effect of the distribution of π^- mesons in range on the number of stoppings in a "thick" target and is found experimentally to be $\beta \leqslant 0.06$; P_H is the probability of atomic capture of mesons by hydrogen in the mixture;

$$q=(1+\varkappa C)/[1+(\Lambda+\varkappa)C]$$

is the probability of nuclear capture of a π^- meson by the proton in a $p\pi^-$ atom in the mixture in the presence of transfer.

The expression for q was obtained phenomenologically[1] on the assumption that in an H_2+Z mixture a π^- meson in a $p\pi^-$ atom is either captured by the proton with a rate $\lambda_p = an_H + dn_Z$ with de-excitation of the mesic atom or is captured into the atom Z with a rate $\lambda_Z = bn_Z$. Here both the de-excitation of the $p\pi^-$ atom and nuclear capture of the π^- meson by the proton, and also the competing transfer of π^- mesons, are determined by collisions of $p\pi^-$ atoms in the mixture. The quantities a, b, and d are constant coefficients, and $\Lambda = b/a$ and $\varkappa = d/a$ are the relative constants for transfer (1) and nuclear capture of the pion by the proton in $p\pi^- + Z$ collisions. Our earlier experimental data[1] were satisfactorily described for $\varkappa = 0$. This means that nuclear capture of the pion by the proton in the $p\pi^-$ atom, induced by collisions of the $p\pi^-$ atom with the atoms Z, has a low probability ($d \sim 0$).

The probabilities of atomic capture of mesons by the components of the gas mixture are proportional to the stopping powers of the atoms[6,7]

$$P_H(C)=1/(1+S_0^H C), \qquad (4)$$

where $S_0^H = B_0^Z/B_0^H$ is the relative stopping power of the atoms Z for the pions being captured. Under the conditions of our experiment (n_H = const) $\Delta_{HZ} = \Delta_H(1+S^H C)$, where S^H is the relative stopping power of the atoms Z averaged over the range of energies of the pions which stopped in the mixture. In our first experiments,[1] where the range of concentrations of heavy atoms (Ne, Ar) investigated was small, it was assumed that $S^H = S_0^H$, and in that case $\alpha(C) = q$. In analysis of the results obtained in the present work under these assumptions and for $\varkappa = 0$ it was found that $\Lambda = A'C^{1/3} + B'$, where A' and B' are constant for each Z. For heavy gases (Kr and Xe), $B' < 0$, which has no physical meaning. The condition $B' > 0$ requires $S^H > S_0^H$. In special measurements with mixtures H_2+N_2 and H_2+Xe at concentrations $C \sim 10^{-3}$, where the contribution of transfer is negligible, we obtained values $\alpha(C) > 1$. This means that $S^H > S_0^H$.

The results were fitted by the expression, obtained from Eqs. (3) and (4),

$$W=1/(1+S_0^H C)(1+\Lambda C) \qquad (5)$$

with two variable parameters Λ and S_0^H; the values of $S^H(C)$ are given in the NBS monograph.[8]

Some of the experimental results are shown in Fig. 2. It turned out that the experimental data are satisfactorily described by expression (5) for

$$\Lambda = AC^{1/3}. \qquad (6)$$

For all gases except CO_2,

$$S_0^H = A = \text{const.} \qquad (7)$$

The values of S_0^H and A obtained for the gases studied are given in the table. It is interesting to note that the values of S_0^H obtained from the experiment are close to the number of electrons in the outer shell of the atom Z (see columns 3 and 4 of the table). This can be considered an indication that in atomic capture of mesons the

Gas	Z	S_0^H	N*	$S_0^{H'}$	$\tilde{S}_0^H$	A
1	2	3	4	5	6	7
He	2	1.84±0.9	2	1.73	1.72±0.13 [9]	1.84±0.9
Ne	10	7.65±0.35	8	7.25	7.1±0.4 [9]	7.65±0.35
Ar	18	11.6±0.4	8	11.8	–	11.6±0.4
Kr	36	16.4±0.60	18	20.0	–	16.4±0.6
Xe	54	20.4±0.7	18	27.6	–	20.4±0.7
N_2	7	6.6±0.3	5	5.5	5.8±0.3 [9]; 6.4±0.4 [7]	6.6±0.3
CO_2	7,3	8.8±1.0	5.3	5.5	8.5±0.7 [9]	3.7±0.6
C (CH_4+H_2)	6	–	4	–	–	4.6±0.3 [10]

*Number of electrons in outer shell of the atom.

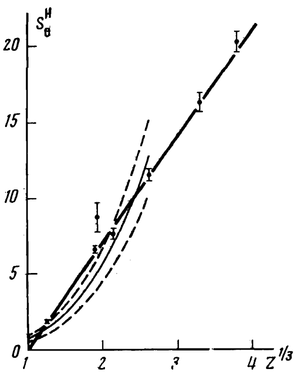

FIG. 3. Relative atomic stopping power S_0^H as a function of Z. The straight line was drawn in accordance with Eq. (8): $S_0^H = (7.1 \pm 0.1)(Z^{1/3} - 1)$. The thin smooth curve shows the function $\Lambda = (0.7 \pm 0.2)Z$, and the dashed curves show the error in its determination (Ref. 1).

electrons of the outer shell of the atom Z take part preferentially. In view of the relation (7) it is natural to suggest that a preferential role in transfer of pions to the atoms Z is played by electrons of their outer shells. For comparison we have given in the table the stopping powers $S_0^{H'}$ calculated by means of data given in Ref. 8, for a pion kinetic energy of 2 MeV, and also values of $\tilde{S}_0^H$ which can be obtained from the data of other studies[9,7] and from our data for Ar and He (see the table). The values of $\tilde{S}_0^H$ obtained in this way are in good agreement with our results.

For all gases except CO_2, the values of S_0^H and Λ are described by a linear dependence on $Z^{1/3}$ (Fig. 3):

$$S_0^H = (7.1 \pm 0.1)(Z^{1/3} - 1), \quad \Lambda = S_0^H C^{1/3}. \qquad (8)$$

Since in the Fermi-Thomas statistical model of the atom, the squares of the atomic radii $r_Z^2 \propto Z^{1/3}$ (Ref. 10), it follows from Eq. (8) that the probability of atomic capture of mesons and the transfer constants Λ in monotonic gases are proportional to the cross sections of the atoms. The very weak dependence of S_0^H on Z is probably due to an appreciable screening of the electrons of the atomic inner shells (particularly in heavy atoms) for the stopping meson.

For pions with a kinetic energy 2 MeV we can expect a smaller effect of screening. In fact, as can be seen from the table, for large Z the value of S_0^H is appreciably less than $S_0^{H'}$. For small Z for all gases except CO_2, S_0^H and $S_0^{H'}$ are nearly the same. For CO_2 the value of S_0^H is almost 1.5 times larger than $S_{0\,\mathrm{int}}^H$, the latter quantity being obtained by interpolation with Eq. (8). The same anomalous increase in the probability of landing of a meson in a CO_2 molecule in gas mixtures was observed previously by Budyashev *et al.*[9] It should be noted that in the interval of change of Z from He to Ar the function $\Lambda(Z)$ determined by Eqs. (6)–(8) agrees within experimental error with our previous result[1] $\Lambda = (0.7 \pm 0.2)Z$.

The extremely weak dependence on Z established in the present work for the pion transfer constant ($\Lambda \propto Z^{1/3}$) is determined by two factors: the existence of a strong interaction in the $p\pi^-$ atom, and the action of the Day-Snow-Sucker mechanism.[12] The combined effect of these two factors has the result that only $p\pi^-$-atom states with rather high excitations take part in the transfer. On the basis of the calculations of Leon and Bethe[13] one can estimate that the transfer occurs from states with quantum numbers $n \lesssim 3$–4.

The dependence of the relative capture rate Λ on the impurity concentration C is apparently due to the fact that transfer occurs from several excited states of the $p\pi^-$ atom. The contribution of each state n to transfer is determined not only by the relation between the capture rate and the rate of de-excitation of the $p\pi^-$ atoms as the result of the external Auger effect, but also by the probability of formation of this state γ_n. With increasing concentration C the contribution of transfer from states with high excitations will increase, which will lead to a depletion of the population of states with smaller excitations, i.e., $\gamma_n = \gamma_n(C)$. Since the transfer cross section increases with the amount of excitation of the $p\pi^-$ atom,[14] this leads to an increase of Λ with concentration C. The same effect will also be produced by a depletion of the population of $p\pi^-$-atom states with small excitations, from which nuclear capture of the π^- meson by the proton mainly occurs ($\sim 1/n^3$).

In fitting the experimental data by Eq. (5), we cannot exclude from consideration the alternative possibility in which $\Lambda = A$ and $S_0^H = AC^{1/3}$, which we consider less likely. This can be done by studying the nuclear capture of pions by the components of gas mixtures in which transfer cannot occur, for example, mixtures $^3He + Z$.[7]

Pion transfer has also been studied by Picard *et al.*[15] and Bugg *et al.*[16] Picard *et al.* studied pion transfer in a mixture $H_2 + Ar$ for a hydrogen pressure of 1 atm and concentrations $C \lesssim 0.1$. In analysis of the data it was assumed that $\Lambda = \mathrm{const}$, and a value $\Lambda = 12.5 \pm 3.9$ was obtained; our value in the same region of C is $\Lambda = 5.4 \pm 0.2$. Bugg *et al.*[16] measured the probability W of nuclear capture of a stopped π^- meson by hydrogen in a solution of Ne in liquid hydrogen ($C = 0.16$); it turned out to be $(17 \pm 5)\%$. According to our data, at a hydrogen density 21 times smaller and $C = 0.16$ the value of W is $(26 \pm 1)\%$.

In spite of the fragmentary nature of the data of Refs. 15 and 16, we can conclude that over a wide range of hydrogen density, from 5×10^{19} cm^{-3} (Ref. 15) to 4.2×10^{22} cm^{-3} (Ref. 16), the dominant transfer mechanism is that determined by collisions of the $p\pi^-$ atom with the atoms or molecules of the mixture.

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Three-reggeon phenomenology in the reaction $p+p \to p+X$

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A statistical analysis has been carried out of data on the reaction $p+p \to p+X$ in the region $|t| < 0.6$ (GeV/c)^2 and $x > 0.85$. All three-reggeon contributions have been taken into account, including the interference terms. Two sets of parameters have been found which characterize the three-reggeon vertices. In order to explain the deviation of the calculated curves from the experimental energy dependence at low energies and the x dependence for $x < 0.85$, a number of diagrams not taken into account in the analysis are proposed. Comparison of the parameter values found with the predictions of the one-pion-exchange model shows good agreement. A discussion is given of a number of processes whose study may provide additional information on the structure of the three-reggeon vertices and the contribution of cuts.

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1. INTRODUCTION

Interest in the experimental and theoretical investigation of the reaction

$$p+p \to p+X \tag{1}$$

at high energies is due to the possibility of carrying out a three-reggeon analysis of the energetic part of the spectra of scattered particles and determining the values of the three-reggeon coupling constants.

The differential cross section for reaction (1) can be related by the unitarity condition to the contribution of three-reggeon diagrams, as shown in Fig. 1, where diagrams with exchange of a pomeron P and reggeons $f=P'$, ω, ρ, and A_2 are summed. In view of the closeness of the trajectories of the second poles, the contributions of the latter are difficult to separate and they are usually replaced by the contribution of an effective pole R.

The expression used in the analysis for the cross section of reaction (1) has the form

$$s\frac{d^2\sigma}{dM^2\,dt} = \sum_{ijk} G_{ijk}(t)\,(1-x)^{\alpha_k(0)-\alpha_i(t)-\alpha_j(t)}\left(\frac{s}{s_0}\right)^{\alpha_k(0)-1} + \left(s\frac{d^2\sigma}{dM^2\,dt}\right)_{\pi\pi P}. \tag{2}$$

Here M is the effective mass of the shower produced, t is the square of the 4-momentum transfer, $x=p_L/p_{\max} \approx 1-M^2/s$ (p_L is the longitudinal component of the momentum of the scattered proton, $p_{\max}$ is its maximum value, and s is the square of the total energy of the colliding particles in the c. m. s.). The last term in Eq. (2) corresponds to the contribution of one-pion exchange and is equal to[1]

$$\left(s\frac{d^2\sigma}{dM^2\,dt}\right)_{\pi\pi P} = \frac{g^2}{(4\pi)^2}\sigma_{tot}^{\pi N}\frac{(-t)}{(\mu^2-t)^2}(1-x)^{1-\alpha_\pi' t}e^{R^2 t}. \tag{3}$$

Here μ is the pion mass, $g^2/4\pi \approx 15$, and $R^2 \approx 3.3$ (GeV/c)$^{-2}$.

The main purpose of the present work is to determine the phenomenological functions $G_{ijk}(t)$ by comparison of Eq. (2) with the experimental data. Preliminary results have been published previously.[2]

Among papers previously published on the questions

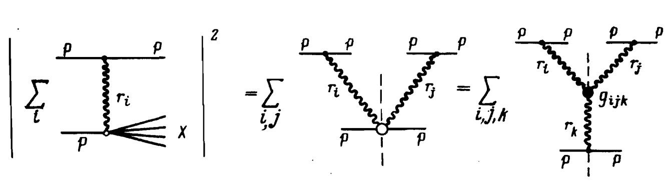

FIG. 1.