

Negative pion transfer process in a hydrogen-containing gas mixture

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Annihilation γ -rays of π^0 and pionic X-rays were measured in the gas mixtures of H_2+Z and CH_4+Z systems ($Z=He, Ne, Ar$ and Kr). Pion capture probability of hydrogen atom was obtained from the annihilation γ -ray counts and the capture probability of Z atom was obtained from the pionic X-ray intensities. Transfer rates were determined from the data based on a combined large mesomolecular model. The transfer rates obtained were smaller than the systematics of the Russian group. Difference in the transfer rate between the gas and the liquid phases was found by a comparison of the present results with our previous ones.

Introduction

When a negative pion enters a material, the pion is slowed down through the interaction with orbital electrons and captured on a highly excited mesoatomic orbital of an atom by Coulomb interaction. The pion capture process in a molecule is influenced by the chemical environment such as the molecular structure and the electron density distribution.¹ The large mesomolecular model (LMM model), which assumed the existence of the large mesomolecular orbital, is successful to explain the capture process in the molecule.^{1,2}

In the molecule containing hydrogen atoms, a pionic hydrogen atom ($p\pi^-$ atom) is isolated from the chemical bond after the capture by hydrogen, because it is small size and neutral. The free $p\pi^-$ atom disintegrates through the charge exchange reaction ($p+\pi^-\rightarrow n+\pi^0$; $\pi^0\rightarrow 2\gamma$) or transfers its pion to one of the neighboring higher Z atoms (transfer process).³

In 1970's, a Russian group studied the transfer process in the mixtures of hydrogen and rare gas.^{4–7} They obtained a systematics for the transfer rate (Λ_Z) from hydrogen atom to other Z atom. They did not obtain the capture probabilities for the H_2 molecule and the rare gas atom, because they only measured the annihilation γ -ray.

Recently, we proposed a new model combining the LMM model and the transfer process (combined LMM model).⁸ The model explained the difference in the capture probabilities of hydrogen atom (W_H) between C_6H_{12} and C_6H_6 in the $C_6H_{12}/C_6H_6+Cl_4/CS_2$ systems.⁹ In this analysis, it was important that the capture rates of each molecule were obtained from the pionic X-ray spectrum.

We measured pionic X-rays as well as annihilation γ -rays in the gas mixtures of H_2+Z and CH_4+Z systems, and tried to obtain the Λ_Z using a similar analysis method to that for liquid mixtures. Then, we compared the obtained Λ_Z with the systematics of the Russian group, and compared those of the CH_4+Z system with our previous results in the liquid phase.

Experimental

The experiments were carried out at a $\pi\mu$ channel of the 12-GeV proton synchrotron in the High Energy Accelerator Research Organization (KEK).¹⁰ The pion beam momentum was 140 MeV/c ($dp/p=2.5\%$) and the beam intensity was typically $2\text{--}5\cdot 10^4$ π^- per second.

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A spectral plot showing the energy distribution of the 100 keV region. The x-axis is labeled 'Energy, keV' and ranges from 0 to 100. The y-axis is labeled 'Counts per channel' and ranges from 0 to 400. The spectrum shows several peaks, with four specific transitions identified and labeled with lines pointing to their respective peaks: C(3-2) at approximately 25 keV, C(4-2) at approximately 28 keV, Ne(4-3) at approximately 52 keV, and Ne(5-3) at approximately 72 keV. The peaks are superimposed on a noisy baseline.

Figure 1 shows the sectional view of the gas chamber. The chamber has cylindrical form to bear high pressure (50 kg/cm^2) and has a sample volume of 125 cm^3 . The 2.5 mm thick chamber wall is made of beryllium to measure the pionic X-rays of carbon (18 keV). The four plastic scintillation counters (PS-1, PS-2, PS-3 and PS-4 (veto)) are mounted in the beam axis to count the numbers of incident and stopped pions in the target. PS-3 and PS-4 are mounted inside the

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target and the other beneath it. Both annihilation γ -rays and pionic X-rays were measured in coincidence with the stop event from the counter telescope.

Samples studied were mixtures of hydrogen and rare gas (He, Ne, Ar or Kr) and mixtures of CH_4 and the rare gas. The content of the rare gas was 10, 20, 30, 40 and 60%. The composition of each sample was analyzed before and after the measurement by gas chromatography. Each sample was measured for 1–20 hours at a pressure of 50 kg/cm².

Figure 2 shows a typical pionic X-ray spectrum for the CH_4 +Ne system. Pionic X-rays for carbon are clearly observed.

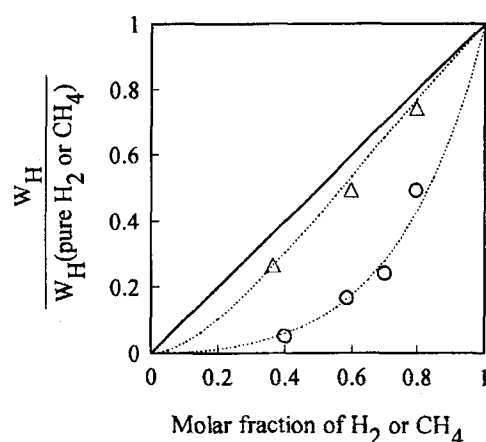


Fig. 3. The relative W_H in the H_2 +Ne and CH_4 +Ne systems. The vertical axis is the relative capture probabilities to that of H_2 or CH_4 . The dotted line is the fitting results using Eq. (3);
○ H_2 +Ne; Δ CH_4 +Ne

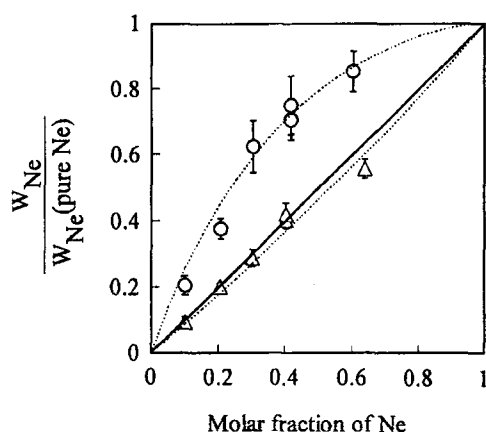


Fig. 4. The relative W_{Ne} in the H_2 +Ne and CH_4 +Ne systems. The vertical axis is the relative capture probability to that of Ne. The dotted line is the fitting results using Eq. (3).
○ H_2 +Ne; Δ CH_4 +Ne

Results and discussion

Results of the capture probabilities

Capture probabilities of hydrogen (W_H) can be obtained from the annihilation γ -rays and those of other Z elements (W_Z) can be obtained from the pionic X-ray intensities. In this analysis, the relative W_H was obtained as the number of the annihilation γ -rays normalized to that of pure H_2 or CH_4 , and the relative W_Z were obtained as the pionic X-ray intensities normalized to that of pure rare gas, in order to cancel several experimental corrections.

The changes of the relative W_H against the molar fraction of H_2 or CH_4 are shown in Fig. 3, and those of Ne against the molar fraction of Ne in Fig. 4 for the H_2 or CH_4 +Ne systems. In the H_2 +Ne system, the relative W_H decreases much from the straight line, and the relative W_{Ne} much increases against the molar fraction of hydrogen atoms (see ○ in Figs 3 and 4). On the other hand, for the CH_4 +Z system, the change seems to be small as shown in Figs 3 and 4. Similar results were obtained for the He, Ar and Kr systems.

The difference in the H_2 and CH_4 system can be explained by the different transfer rates for different atomic states of $p\pi^-$ atoms.

Analysis based on the combined LMM model

We can derive the transfer parameters from the dependence of W_H and W_Z on the hydrogen fraction based on the following formula,

$$W_H = \frac{M_\alpha}{M_\alpha + K(1 - M_\alpha)} W_H(\alpha) \frac{1}{1 + \sum \Lambda_{Zi} C_{Zi}} \quad (1)$$

$$W_Z = \frac{K(1 - M_\alpha)}{M_\alpha + K(1 - M_\alpha)} W_Z(\beta) + \frac{M_\alpha}{M_\alpha + K(1 - M_\alpha)} W_H(\alpha) \frac{\Lambda_Z C_Z}{1 + \sum \Lambda_{Zi} C_{Zi}} \quad (2)$$

for the $\alpha(\text{H})+\beta$ system, where Λ_Z is the reduced transfer rate for Z atoms, C_Z is the ratio of the number of Z atom to hydrogen atom, K is the ratio of the pion capture rate of α -molecules to β -molecules, and M_α is the molar fraction of α -molecule in the mixture. The first factor in the formula corresponds to the capture fraction between α and β molecules. $W_H(\alpha)$ is the probability for formation of the $p\pi^-$ atom within an α -molecules, and $W_Z(\beta)$ is the capture probability of Z-atom within β -molecules. These probabilities can be estimated with a combined LMM model.⁸ The third factor in Eq. (1) means the non-transfer probability.

We can analyze the data without consideration of W_H , W_Z and several experimental corrections by taking the relative W_H values to that of pure H_2 or CH_4 , as shown in Figs 3 and 4. As for the W_H value, Eq. (1) can be written as

$$\frac{W_H}{W_H(\text{pure } \alpha)} = \frac{M_\alpha}{M_\alpha + K(1 - M_\alpha)} \frac{1}{1 + \sum \Lambda_{Zi} C_{Zi}} \quad (3)$$

In the analysis of the W_Z in the CH_4 systems, we can neglect the contribution from the transfer in Eq. (2), because the contribution is very small compared to the probability of the initial capture by the Z-atoms (the first factor in Eq. (2)). Then we can simplify Eq. (2) by taking the relative value to the pure β -molecule as follows,

$$\frac{W_Z}{W_Z(\text{pure } \beta)} = \frac{K(1 - M_\alpha)}{M_\alpha + K(1 - M_\alpha)} \quad (4)$$

Using Eq. (4), we can determine the capture rate ratio K from the obtained pionic X-ray data (see Fig. 4) as for the CH_4 systems. The Λ_Z values were obtained from the fitting of W_H values to Eq. (3) using the obtained K values and $\Lambda_C = 1.7$; this value was obtained from the results of alkanes.⁸ In the H_2 systems, however, we could not determine these parameters using Eqs (3) and (2) because of the complexity of Eq. (2) and large experimental errors of the W_H and W_Z values. Then, the 2γ events per incident pion were used for the analysis of Λ_Z , where the relative 2γ events of hydrogen in the mixture was assumed to be proportional to the partial pressure relative to the pure hydrogen sample. The K values for the H_2 systems were obtained using Eq. (2) from the determined Λ_Z and the pionic X-ray data (see Fig. 4). The results of the analysis were summarized in Table 1.

Table 1. The relative capture rate and the transfer rate of CH_4+Z and H_2+Z systems

Noble gas (Z)	CH ₄ +Z system		H ₂ +Z system	
	K	Λ_Z	K	Λ_Z
He	—	1.5±0.3	—	1.2±0.2
Ne	0.68±0.07	2.4±0.2	2.7±0.5	5.5±0.6
Ar	0.87±0.11	3.6±0.4	3.5±0.6	7.7±0.7
Kr	1.8±0.4	4.0±0.6	8.5±1.1	9.0±0.7

Comparison of the present results with the systematics of the Russian group and our previous results

Figure 5 shows the Z dependence of the transfer rate parameter to compare our results (Table 1) with the Horváth's and Russian's systematics^{3,6} and our previous results for liquid phase. The experimental results of H_2+Z systems are systematically smaller than the estimates by the Russian's systematics, and the experimental results of CH_4+Z systems are also smaller than the estimates by the Horváth systematics. We obtained the capture rate for individual molecule from the X-ray measurements, while the Russian's group assumed that the capture rates were proportional to the stopping power of the atoms.⁸ Table 2 presents a comparison among the observed K values, the prediction by the LMM model, and the estimates by the Russian's systematics. The LMM model calculations are close to the observed K values, and the Russian's systematics is far from our results. This fact may cause the difference in Λ_Z .

Table 2. The ratio of the capture rate to that of hydrogen

Noble gas (Z)	Present results	LMM model*	Systematics**
Ne	2.7±0.5	4	8.2
Ar	3.5±0.6	4	11.5
Kr	8.5±1.1	9	16.3

* According to the LMM model, the capture probabilities are proportional to the numbers of loosely bound electrons. We assumed that the electrons with binding energies lower than 100 eV, contributed to the capture process.

** Taken from Ref. 7.

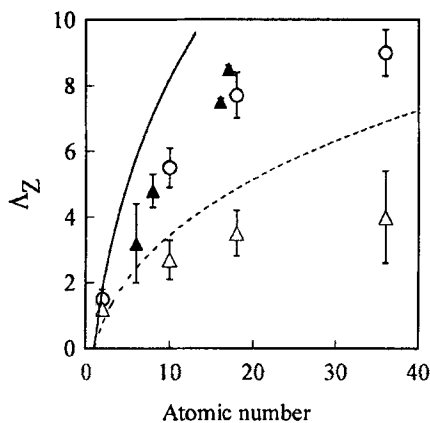


Fig. 5. Comparison of the Λ_Z of our experiments with those from the systematics. \circ H_2+Z system; Δ CH_4+Z system; \blacktriangle our previous results. Solid line: Russian's systematics, dashed line: Horváth's systematics

The experimental results of CH_4+Z systems are also smaller than our previous results for the alkanes mixtures in liquid phase.⁸ These experiments were carried out with same method. The results may be related to the different in density between the gas and liquid phases in the transfer process.

Conclusions

We measured the annihilation γ -rays of π^0 and pionic X-rays in H_2+Z and CH_4+Z systems (Z : He, Ne, Ar and Kr), and obtained W_H and W_Z . The transfer rate of He, Ne, Ar and Kr in H_2+Z and CH_4+Z systems were determined based on the revised LMM model.

The obtained transfer rates were smaller than the estimates of the Russian group. The transfer rates of the CH_4+Z system were also smaller than our results for liquid phase.

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References

1. L. I. PONOMAREV, *Ann. Rev. Nucl. Sci.*, 23 (1973) 395.
2. H. SCHNEUWLY, V. I. POKROVSKY, V. I. PONOMAREV, *Nucl. Phys.*, A312 (1978) 419.
3. D. HORVÁTH, *Radiochim. Acta*, 28 (1981) 241.
4. V. I. PETRUKHIN, YU. D. PROKOSHJIN, V. M. SUVOROV, *Zh. Eksp. Teor. Fiz.*, 55 (1968) 2173 [*Sov. Phys. JETP*, 28 (1969) 1151].
5. V. I. PETRUKHIN, V. E. RISIN, V. M. SUVOROV, *Yad. Fiz.*, 19 (1973) 626 [*Sov. J. Nucl. Phys.*, 19 (1974) 317].
6. V. I. PETRUKHIN, V. E. RISIN, I. F. SAMENKOVA, V. M. SUVOROV, *Zh. Eksp. Teor. Fiz.*, 69 (1975) 1883 [*Sov. Phys. JETP*, 42 (1976) 955].
7. V. I. PETRUKHIN, V. M. SUVOROV, *Zh. Eksp. Teor. Fiz.*, 70 (1976) 1145 [*Sov. Phys. JETP*, 43 (1977) 595].
8. A. SHINOHARA, T. MUROYAMA, J. SHINTAI, J. KURACHI, M. FURUKAWA, T. MIURA, Y. YOSHIMURA, T. SAITO, T. OHDAIRA, N. IMANISHI, *Phys. Rev. A*, 53 (1996) 130.
9. A. SHINOHARA, T. MUROYAMA, T. MIURA, T. SAITO, A. YOKOYAMA, M. FURUKAWA, *Hyp. Int.*, 106 (1997) 301.
10. K. H. TANAKA, Y. KAWASHIMA, J. IMAZATO, M. TAKAHASHI, H. TAMURA, M. IWASAKI, E. TAKADA, R. S. HAYANO, M. AOKI, H. OOTA, T. YAMAZAKI, *Nucl. Instr. Meth.*, A316 (1992) 134.