

CHLORINE-38 FOR CHLORINE SUBSTITUTION IN GEOMETRIC
AND DIASTEREOMERIC COMPOUNDS: MECHANISM
AND STEREOCHEMISTRY

by

Tobias Ralph Acciani

Dissertation submitted to the Graduate Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

Chemistry

APPROVED:

Hans J. Ache, Chairman

Michael A. Ogliaro

John C. Schug

Jimmy W. Viers

Hampton P. Smith

August, 1977
Blacksburg, Virginia

II. ACKNOWLEDGMENTS

I would like to express my sincere gratitude and appreciation to my research advisor, _____, for his constant support and guidance throughout the course of this investigation; to my committee members, _____ and _____; and to _____ and _____ for their time and help.

I would like to thank _____ and _____ for the construction and repair of various glass equipment; and, to _____ and _____ for repair of the electrical equipment.

A sincere thank you to _____ for his help in measuring the NMR spectra of the various compounds and to _____ for his help with the computer programs.

I would also like to thank the various members of _____ research group for their help and friendship throughout the course of this investigation and _____

A final thank you to _____ for allowing me to use his research laboratory at University of North Carolina in order to take the dipole moments of the various compounds and his graduate student _____ for showing me how to run the Dipolmeter.

III. TABLE OF CONTENTS

CHAPTER	PAGE
I. TITLE	i
II. ACKNOWLEDGMENTS	ii
III. TABLE OF CONTENTS	iii
IV. LIST OF TABLES	viii
V. LIST OF FIGURES	xi
VI. STATEMENT OF PURPOSE OF RESEARCH INITIATED IN THIS THESIS	1
VII. BASIC PRINCIPLES OF HOT ATOM CHEMISTRY	3
A. Introduction	3
B. Formation of Hot Atoms by Nuclear Recoil Following (n, γ) Reactions	6
C. Charge State of Recoil Atoms	9
D. Definitions and Criteria for Hot Reactions	13
E. Cage Reactions	17
F. Mechanisms in Hot Atom Chemistry	22
1. Billiard ball collision-epithermal collision	22
2. Random fragmentation	24
3. Impact	25
4. Direct replacement with collisional stabil- ization of caged complex model	28
G. Stereochemistry	30

CHAPTER	PAGE
H. Conformational Effect	36
VIII. EXPERIMENTAL	41
A. Purification of Starting Materials	41
1. Meso and racemic 1,2-dichloro-1,2-difluoro-ethane	41
2. <u>Cis</u> and <u>trans</u> -1,2-dichlorohexafluoroethane	41
3. Commercial materials	44
B. Sample Preparation and Irradiation Procedure	44
1. ³ H for H substitution in 1,2-dichloro-1,2-difluoroethane	44
2. ³⁸ Cl for Cl substitution in 1,2-dichloro-1,2-difluoroethane	44
3. ³⁸ Cl for Cl substitution in 1,2-dichlorohexafluorocyclobutane	45
C. Gas Chromatographic Analysis of Neutron Irradiated Samples	45
1. ³⁸ Cl for Cl and/or ³ H for H substitution in 1,2-dichloro-1,2-difluoroethane	45
2. ³⁸ Cl for Cl substitution in 1,2-dichlorohexafluorocyclobutane	46
D. Radioactivity Measurements	47
1. ³⁸ Cl for Cl substitution in 1,2-dichloro-1,2-difluoroethane and 1,2-dichlorohexafluorocyclobutane	47

CHAPTER	PAGE
2. ^3H for H substitution in 1,2-dichloro- 1,2-difluoroethane	47
E. Determination of the Retention to Inversion Ratio	48
F. Conformational Analysis	51
1. General principles	51
2. Experimental conditions for ^1H and ^{19}F NMR of meso and racemic 1,2-dichloro- 1,2-difluoroethane	56
3. Experimental conditions for ^{19}F NMR of <u>cis</u> and <u>trans</u> 1,2-dichlorohexafluorocyclobutane.	57
G. Conformational Population of Meso 1,2-dichloro- 1,2-difluoroethane	57
H. Determination of Experimental Molecular Dipole Moments for Meso and Racemic 1,2-dichloro- 1,2-difluoroethane	59
I. Experimental Conditions for the Determination of Molecular Dipole Moments	62
J. Determination of Conformer Dipole Moments of Meso and Racemic 1,2-dichloro-1,2-difluoro- ethane	62
IX. RESULTS	66
A. ^3H for H Substitution in Meso 1,2-dichloro- 1,2-difluoroethane	66
B. ^{38}Cl for Cl Substitution in 1,2-dichloro-	

CHAPTER	PAGE
hexafluorocyclobutane	66
C. ³⁸ Cl for Cl Substitution in 1,2-dichloro-	
1,2-difluoroethane	68
D. Calculation of Conformer Dipole Moments for Meso	
and Racemic 1,2-dichloro-1,2-difluoroethane . .	73
E. Experimental Molecular Dipole Moments	74
1. Meso and racemic 1,2-dichloro-1,2-difluoro-	
ethane	74
2. <u>Cis</u> and <u>trans</u> 1,2-dichlorohexafluorocyclo-	
butane	77
F. Conformational Population of Meso 1,2-dichloro-	
1,2-difluoroethane	77
G. Conformational Population of Racemic	
1,2-dichloro-1,2-difluoroethane	77
H. Effect of Solvent Concentration on Conformer	
Population of Meso 1,2-dichloro-1,2-difluoro-	
ethane	86
I. Temperature Effect on Conformer Population of	
Meso and Racemic 1,2-dichloro-1,2-difluoro-	
ethane	86
J. Conformational Population of <u>Cis</u> and <u>Trans</u>	
1,2-dichlorohexafluorocyclobutane	89
K. Summary of Conformational Analysis	91
X. DISCUSSION	93
A. Introduction	93

CHAPTER	PAGE
B. ^3H for H Substitution in 1,2-dichloro- 1,2-difluoroethane	95
C. ^{38}Cl for Cl Substitution in 1,2-dichloro- 1,2-difluoroethane and 1,2-dichlorohexafluoro- cyclobutane	98
D. Summary	114
XI. LITERATURE CITED	115
XII. APPENDIX A	119
XIII. APPENDIX B	124
XIV. VITA	128

IV. LIST OF TABLES

TABLE	PAGE
I. Properties of Recoil Halogens Generated by Neutron Capture	10
II. Comparison of Intrinsic Properties of Thermal versus Hot Reactions	14
III. Previous Results of ^3H for H Substitution at Asymmetric Carbon Atoms	31
IV. Previous Results of Recoil Halogen for Halogen Substitution at Asymmetric Carbon Atoms	32
V. Conditions Employed in the Gas Chromatographic Separation of Diastereomeric 1,2-dichloro-1,2-difluoroethane	42
VI. Conditions Employed in the Gas Chromatographic Separation of the Geometric Isomers of 1,2-dichlorohexafluorocyclobutane	43
VII. Comparison Between ^1H and ^{19}F NMR Experimental Coupling Constants (Hertz) for Meso and Racemic 1,2-dichloro-1,2-difluoroethane	58
VIII. Comparison Between the Experimental Coupling Constants (Hertz) of R. J. Abraham and This Research for Meso and Racemic 1,2-dichloro-1,2-difluoroethane	60
IX. Structural Parameters for the Calculation of Conformer	

TABLE	PAGE
Dipole Moments of Meso and Racemic 1,2-dichloro- 1,2-difluoroethane	65
X. Percent Retained Product in ^3H for H Substitution in Meso 1,2-dichloro-1,2-difluoroethane	67
XI. Retention/Inversion Ratio in ^{38}Cl for Cl Substitu- tion in <u>Trans</u> 1,2-dichlorohexafluorocyclobutane . . .	69
XII. Retention/Inversion Ratio in ^{38}Cl for Cl Substi- tution in <u>Cis</u> 1,2-dichlorohexafluorocyclobutane . . .	70
XIII. ^{38}Cl for Cl Substitution in Meso 1,2-dichloro-1,2-di- fluoroethane	71
XIV. ^{38}Cl for Cl Substitution in Racemic 1,2-dichloro- 1,2-difluoroethane	72
XV. Experimental Molecular Dipole Moments of Meso and Racemic 1,2-dichloro-1,2-difluoroethane (Cyclohexane Was Used As Standard)	75
XVI. Comparison of Calculated to Experimental Molecular Dipole Moments of Meso and Racemic 1,2-dichloro- 1,2-difluoroethane in Cyclohexane	76
XVII. Experimental Molecular Dipole Moments of <u>Cis</u> and <u>Trans</u> 1,2-dichlorohexafluorocyclobutane	78
XVIII. Conformer Population for Meso 1,2-dichloro-1,2-di- fluoroethane	79
XIX. Experimental Coupling Constants(Hertz) for Meso 1,2-dichloro-1,2-difluoroethane	80
XX. Conformer Population for Racemic 1,2-dichloro-	

TABLE	PAGE
1,2-difluoroethane	81
XXI. Experimental Coupling Constants (Hertz) for Racemic	
1,2-dichloro-1,2-difluoroethane	83
XXII. Concentration Effect on Conformer Population of Meso	
1,2-dichloro-1,2-difluoroethane	87
XXIII. Temperature Effect on Conformer Population of Meso and	
Racemic 1,2-dichloro-1,2-difluoroethane	88
XXIV. ¹⁹ F NMR of <u>Cis</u> and <u>Trans</u> 1,2-dichlorohexafluoro-	
cyclobutane	90

V. LIST OF FIGURES

FIGURE	PAGE
1.	Reaction Cross Sections as a Function of the Kinetic Energy of Atomic Hydrogen (X) with Arbitrary Compound RH 4
2.	$^{37}\text{Cl}(n,\gamma)^{38}\text{Cl}$ Nuclear Reaction 8
3.	Effect of I_2 Scavenger on ^{128}I for I Substitution in Ethyl Iodide 16
4.	Effect of He Moderation of Recoil Tritium in Propane . 18
5.	Richardson and Wolfgang, Absolute Yields of ^{18}F for H and ^{18}F for F Substitution in CH_3F Are Measured as a Function of Densities 21
6.	Modes of Reactions of Hot Hydrogen Atoms 26
7.	Density Effect in ^{38}Cl for Cl Substitution in Meso and Racemic 1,2-dichloro-1,2-difluoroethane 34
8.	Density Effect in ^3H for H Substitution in Meso and Racemic 1,2-dichloro-1,2-difluoroethane 35
9.	Solvent Effect on the Stereochemical Course of ^{38}Cl for Cl Substitution in 2,3-dichlorobutanes 37
10.	Conformational Effect on the Stereochemical Course of ^{38}Cl for Cl Substitution in Meso 2,3-dichlorobutane . . 39
11.	Conformational Effect on the Stereochemical Course of ^{38}Cl for Cl Substitution in Racemic 2,3-dichloro-

FIGURE	PAGE
butane	40
12. Comparison Between Gas Chromatogram and Radioactivity Graph	50
13. Most Stable Conformers of Meso and Racemic 1,2-dichloro-1,2-difluoroethane	53
14. Conformers of <u>Cis</u> and <u>Trans</u> 1,2-dichlorohexafluoro- cyclobutane	55
15. Change in Dielectric Behavior of a Solution of Meso 1,2-dichloro-1,2-difluoroethane and cyclobutane as a Function of Mole Fraction	63
16. Comparison of $^3J_{\text{HH}(\text{trans})}$ and $^3J_{\text{HH}(\text{gauche})}$ Coupling Constants in Tetrahaloethanes	85
17. Density Effect on Substitution Product Yield	96
18. Conformational Population of Meso 1,2-dichloro- 1,2-difluoroethane as a Function of Dielectric Constant of Solvent	101
19. Conformational Population of Racemic 1,2-dichloro- 1,2-difluoroethane as a Function of Dielectric Constant	102
20. Conformational Population of Meso 1,2-dichloro- 1,2-difluoroethane as a Function of the Retention to Inversion Ratio of Meso 1,2-dichloro-1,2-difluoro- ethane	103
21. Conformational Population of Racemic 1,2-dichloro- 1,2-difluoroethane as a Function of the Retention to	

FIGURE	PAGE
Inversion Ratio of Racemic 1,2-dichloro-1,2-difluoroethane	104
22. Interaction Term $(\epsilon - 1)/(2\epsilon + 1)$ of Solvents as a Function of the Retention to Inversion Ratio of Meso 1,2-dichloro-1,2-difluoroethane	108
23. Interaction Term $(\epsilon - 1)/(2\epsilon + 1)$ of Solvents as a Function of the Retention to Inversion Ratio of Racemic 1,2-dichloro-1,2-difluoroethane	109

DEDICATION

TO MY PARENTS, MARGARET AND DANIEL ACCIANI
FOR THEIR CONSTANT LOVE, UNDERSTANDING
AND GUIDANCE

VI. STATEMENT OF PURPOSE OF RESEARCH INITIATED IN THIS THESIS

Gas phase hot halogen for halogen substitution reactions proceed predominately with retention of configuration (about 90 percent)^{1,2,3} and can be explained in terms of a one step substitution mechanism. The stereochemical course for the same reaction in liquid phase, however, can be varied over a wide range (from 50 to 90 percent retention)^{4,5,6} by changing the type and concentration of the solvent. This result indicates that the hot atom substitution reaction in the liquid phase follows a more complicated reaction scheme.

Solvents could possibly affect substitution reactions in two ways: (1) indirectly by inducing variations in the relative conformer population; and, (2) directly by participating in the de-excitation-stabilization of excited compounds or relaxation processes of fragments, radicals, etc.

Thus, experiments were designed to determine how solvents control the stereochemical course of the substitution reaction. Two systems were chosen to examine the mechanism of the ³⁸Cl for Cl substitution, the 1,2-dichloro-1,2-difluoroethane isomers and the 1,2-dichlorohexafluorocyclobutane isomers. In each system the conformer population can be determined by NMR techniques. A comparison of the changes of the stereochemical course of the substitution reaction should follow by varying the concentration and nature of

the solvent to reach a conclusion as to the contribution made by each one of the two effects on the overall substitution process.

In summary, the main objectives of this research are to:

(1) determine what factors control the course of a hot atom substitution reaction; (2) present a mechanism or mechanisms for hot atom substitution reactions; and, (3) produce the highest yield and purest radioactive labelled compounds.

VII. BASIC PRINCIPLES OF HOT ATOM CHEMISTRY

A. Introduction

Atoms which possess high translational energies generated from nuclear processes, such as radioactive neutron capture (n, γ) are called hot atoms and are not in thermal equilibrium with the chemical environment. The energy range for hot atoms is from just above thermal to a few MeV. Reactions of hot atoms are often different from thermal reactions. In thermal reactions, the activation energy requirement limits the number of available reaction pathways for the reactants, thus certain reactions are forbidden at thermal energies. In hot atom reactions, there is sufficient energy in the system so that more reaction pathways are available, thus a larger variety of products are formed. Hot atom chemistry is concerned with the study of reactions of atoms over the entire kinetic energy range in which chemical reactions occur.

Figure 1 shows a hypothetical dependence of the probability of forming certain products or excitation functions for the reaction paths leading to various possible products as a function of the kinetic energy of an atomic hydrogen (X) with an arbitrary compound RH. In thermal systems, only the threshold reaction path leading to HX will be significant. Conversely, a hot atom of a given energy (E') could react by all the indicated paths.⁷

Hot atoms can be produced by photolysis of suitable molecules,

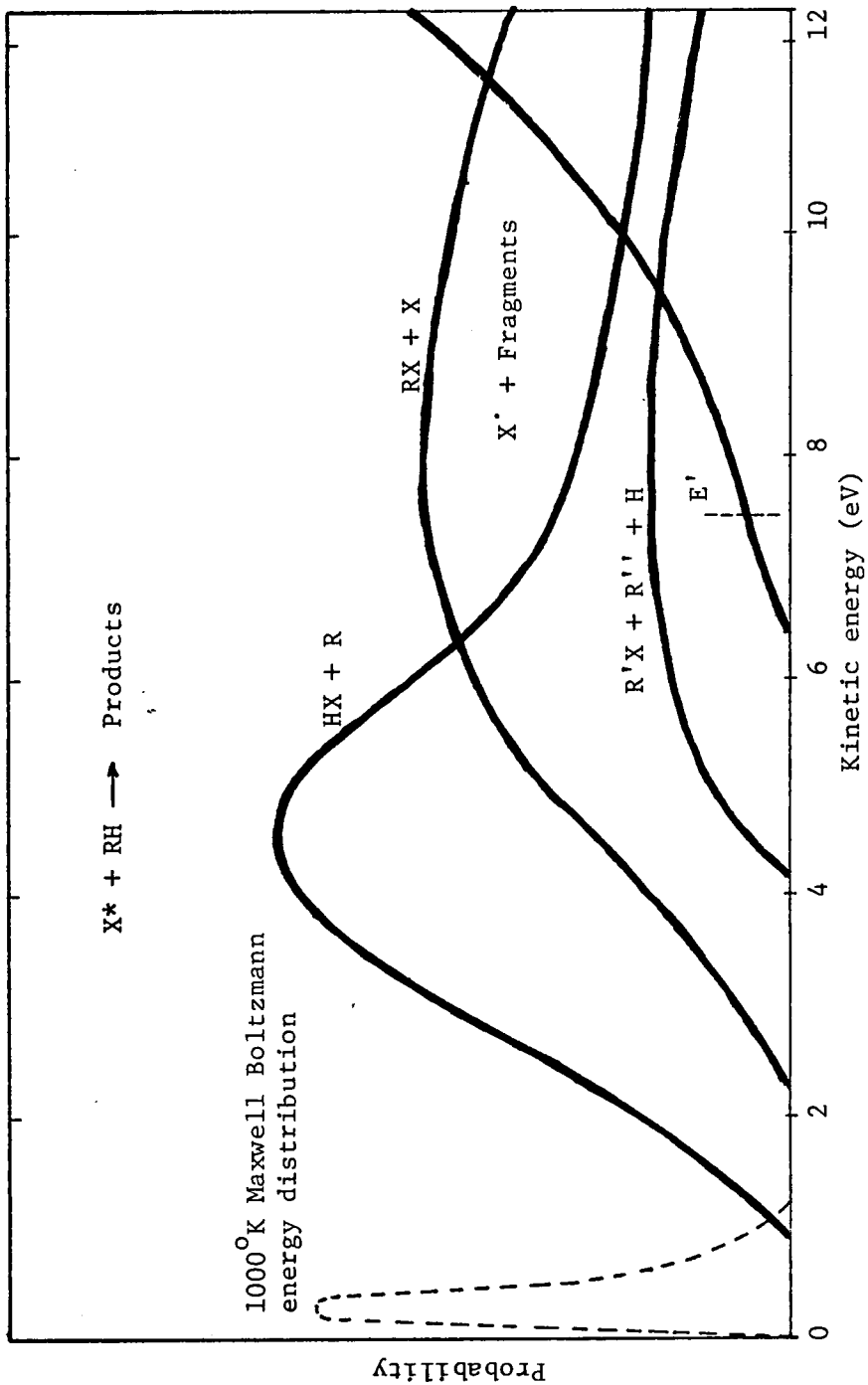


Figure 1. Reaction Cross Sections as a Function of the Kinetic Energy of Atomic Hydrogen (X) with Arbitrary Compound RH*

* taken from reference 7

by ultraviolet light, by accelerators and by nuclear transformations. Methods such as photolysis and accelerators have major limitations: namely, they can generate hot atoms only in the gas phase within a narrow energy range. Nuclear transformations like (n,γ) , β -decay, etc., have a greater versatility. This method can be employed in all three phases of matter and the energy ranges for recoil atoms reach from just above thermal to a few thousand eV. Other advantages are: the hot atom produced is radioactive; it allows subsequent detection of labelled products by virtue of the radioactive atom incorporated in the molecule; extremely sensitive detection techniques are available. Furthermore, since about 10^8 hot atoms will typically be produced in the presence of about 10^{20} molecules of substrate, the chances of producing a molecule with a doubly substituted product are very unlikely. Nuclear transformation is the technique employed for the production of hot atoms in the research.

The first study of chemical effects of nuclear transformations was done by Szilard and Chalmers in 1934.⁸ Their experiments showed that radioactivity could be extracted in the inorganic form from a halogenated organic compound which had been irradiated by neutrons. A year later, Amaldi and others concluded that the energy of the gamma ray recoil was sufficient to eject the active atom from its initial position in the molecule.⁹ Gluckauf and Fay, in 1936, showed that new organic compounds containing radioactive elements could be produced by Szilard and Chalmers reactions.¹⁰ Since then, reactions of recoil halogens generated by nuclear

processes (n, γ) have been subject to a large number of investigations.¹¹⁻²⁰

B. Formation of Hot Atoms by Nuclear Recoil Following (n, γ) Reactions

Since there is no Coulombic barrier to be surmounted, it is possible for neutrons to enter into a target nucleus and form a compound nucleus. In the compound-nucleus model, it is assumed that the energy carried by the neutron is randomly distributed among all the nucleons. The excitation energy of the compound nucleus, formed by neutron capture by a target nucleus, is in most cases the same as the binding energy of the captured neutron, and thus a nucleon usually does not have enough energy to escape. Therefore, the compound nucleus will exist for a period between 10^{-14} to 10^{-18} seconds before the excess excitation energy is emitted in the form of gamma rays.²¹ As the result of the emission of a gamma ray, the newly formed nucleus undergoes recoil with considerable kinetic energy.

In thermal neutron capture, a 0.025 eV incident neutron will excite the nucleus to about six to eight MeV and a large fraction of this energy is dissipated by the emission of one or more gamma rays. Because of the laws of conservation of momentum and energy, the recoil energy can be expressed as

$$E_r = \frac{E_\gamma^2}{2 M C^2} \quad (1)$$

where M is the mass in atomic units, E_r is the recoil energy in eV,

C is the speed of light, and E_γ is the gamma ray energy in MeV. A nucleus will recoil as a result of the photon emission with more than sufficient energy for the rupture of one or more bonds.

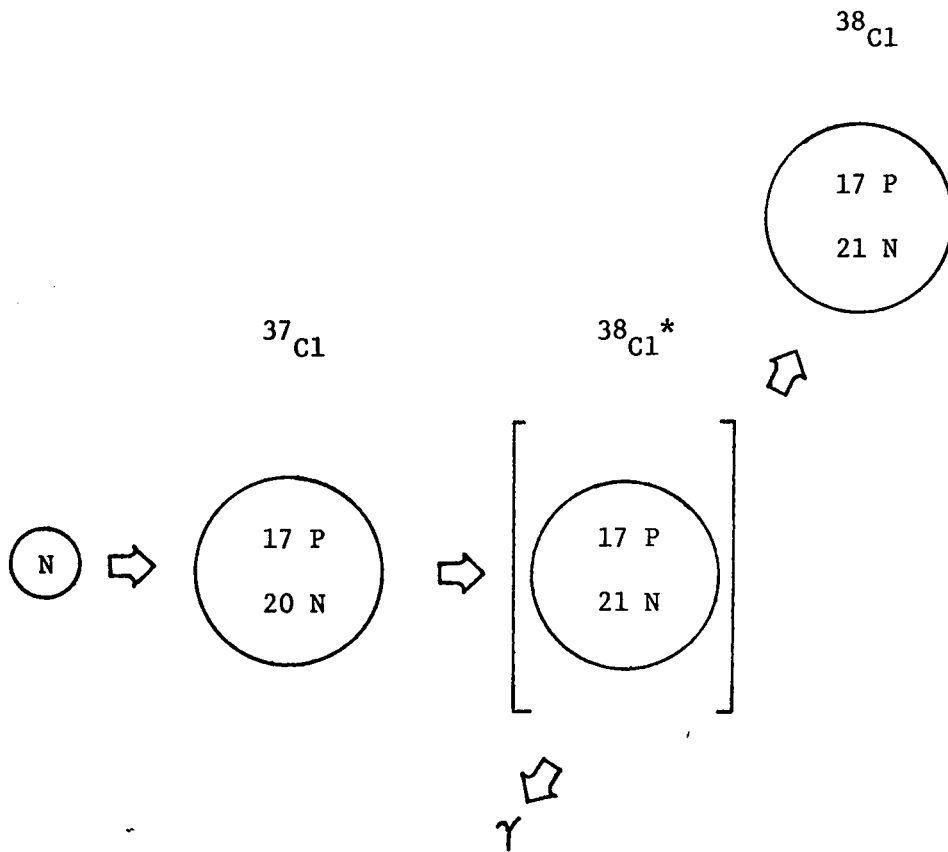
Assuming that the excess energy is emitted as a single gamma ray, Equation (1) becomes

$$E_r = \frac{537 E_\gamma^2}{M} \quad (2)$$

Since gamma rays are emitted in cascade and in different directions, some cancellation of recoil may occur. As a result, the recoil energy available is considerably smaller, but still large enough to break chemical bonds.²¹ As an example, the nuclear reaction $^{37}\text{Cl}(n,\gamma)^{38}\text{Cl}$ is described in detail in Figure 2.

The calculated recoil energy of ^{38}Cl in Figure 2 is misleading because it involves only a single chlorine atom undergoing an (n,γ) reaction. In hot atom chemistry, the chlorine atom is bound to a molecule; therefore, a considerable amount of the recoil momentum is absorbed by the whole molecule not just the chlorine atom. Also, a certain amount of recoil energy must be spent in order to break the chlorine bond in the molecule. Therefore, the recoil hot atom will have considerably less than 537 eV. Because each individual molecule to which a chlorine is bound will absorb varying amounts of the recoil momentum, the recoil hot atom will have a wide energy spectrum.

The induced activity at the end of the irradiation can be calculated by the following equation:²²



$$E_{\gamma} = 6.11 \text{ MeV}$$

$$\text{Recoil Energy } E_r = \frac{537 E_{\gamma}^2}{M} = 528 \text{ eV (max)}$$

Figure 2. $^{37}\text{Cl}(n,\gamma)^{38}\text{Cl}$ Nuclear Reaction

$$S = \frac{0.6025 \sigma k}{A \phi [1 - \exp(-\lambda t)]} \quad (3)$$

where S is the induced activity expressed in disintegrations per second per gram, σ is the cross section of the reaction, k is the fractional abundance of the isotope, A is the mass of the target element, λ is the decay constant of the nuclear species produced, t is the irradiation time, and ϕ is the neutron flux in units of neutrons per centimeter² per second². Table I outlines the properties of some recoil atoms, induced by neutron capture, which are commonly used in hot atom chemistry.

C. Charge State of Recoil Atoms

Three factors determine the final state of hot atoms: (1) its primary state as it is produced by the initial nuclear transformations; (2) the charge exchange reactions occurring while the species is recoiling; and, (3) the possibility of ionization occurring subsequent to recoil because of delayed nuclear processes.

The initial state of a recoil species produced by nuclear transformation in the KeV range is an atom stripped of one or more electrons. However, recoil species in the KeV energy range or higher undergo so many charge exchange collisions that the hot atom's initial charge state is irrelevant.²³

In the KeV energy range or higher, hot atoms produced by nuclear recoil behave like any other particulate ionizing radiation. The hot atom is rapidly stripped of those electrons with

orbital velocities less than the translational velocity; energy is lost by electronic excitation and ionization of the medium. As the velocity of the particle decreases with respect to the orbital electron velocities, it becomes neutral. Bethe,²⁴ Bohr²⁵ and others²⁶ have given a theoretical picture of the stopping of high energy particles.

The adiabatic hypothesis, or resonance rule,²⁷ has proven very useful for predicting the charge state of recoil species in the chemical bond region (10 eV). This hypothesis states that the probability for electronic transition during a collision will be a maximum when the time of the collision equals the period of the transition.

The maximum probability of transition occurs when

$$\frac{a E}{h v_{\max}} = 1 \quad (4)$$

where E is the energy of transition, h is Plank's constant, a is the average relative distance of travel by a hot atom before collision (7×10^{-8} cm), and v_{\max} is the maximum relative velocity. Equation (4) is the adiabatic hypothesis. The maximum kinetic energy of the hot atom is given by

$$E_{\max} = \frac{1}{2} m v_{\max}^2 \quad (5)$$

The adiabatic hypothesis has been used for predicting the charge state of recoil ^3H , ^{11}C , ^{39}Cl , and ^{127}I .²⁸⁻³¹ High energy (10^4 eV) recoil ions, such as those from particle emission (n,2n) and (n,p), can be expected to reach chemical energies as atoms. On the other hand, recoil atoms produced by (n, γ) reactions are in the energy

range of hundreds of eV and undergo only a few collisions before they react; thus the final state of the recoil species might depend on the initial state. However, if the de-excitation process includes low energy gamma rays, a high probability for internal conversion exists, which is followed by Auger emission resulting in Coulombic explosion. Consequently, a significant fraction of the species produced by (n,γ) processes are ionized and not all may become neutralized before they react.^{32,33}

Reionization subsequent to recoil is a possibility because the nucleus may be left in a metastable level which de-excites after recoil. Internal conversion would be one of the possible processes leading to reionization. The metastable nuclear level must be longer lived than the time of the recoil and would therefore have to de-excite by a more or less forbidden transition of relatively low energy. This situation will usually occur for higher mass nuclei produced by (n,γ) reactions.³¹

Recoil tritium and recoil ^{38}Cl were both used as the hot atoms for this research. The charge state of tritium is a neutral atom because of its high recoil energy of 2.7 MeV for the $^6\text{Li}(n,\alpha)^3\text{H}$ reaction. The charge state for the ^{38}Cl is not so straightforward because it is in the lower energy range (just above thermal to a few hundred eV).

In order to establish the charge state of ^{38}Cl , one can examine the reaction of ^{39}Cl . Recoil ^{39}Cl produced by $^{40}\text{Ar}(\gamma,p)^{39}\text{Cl}$ has an energy of 0.27 MeV; therefore, it will become neutralized before chemical reaction takes place. Since Rowland and Wai³⁴

have shown that there were no significant differences between the reactions of ^{38}Cl and ^{39}Cl with d,l and meso-2,3-dichlorobutane, methyl chloride and cis-1,2-dichloroethylene, it appears that in both types of experiments the same neutral halogen participated in the reaction. Moderator experiments were also run on both ^{38}Cl and ^{39}Cl , which lead to the conclusion that ^{38}Cl reacts as an atom. Reactions of ^{38}Cl with n-propyl- and isopropyl-chloride show still more evidence which supports the claim that ^{38}Cl reacts as an atom.^{35,36}

The existence of $^{38\text{m}}\text{Cl}$ ($t_{1/2} = 0.74$ seconds) introduces a negligible effect on the use of ^{38}Cl as a reaction source for energetic Cl atoms.³⁴ The decay of $^{38\text{m}}\text{Cl}$ is entirely by 0.66 MeV gamma ray emission to ^{38}Cl , internally converted in only a fraction of (5×10^{-4}) of the decays. The recoil energy resulting from the emission of a 0.66 MeV gamma ray is 61 eV while the cross section for the formation of the $^{38\text{m}}\text{Cl}$ in the (n, γ) process is estimated³⁴ to be only one percent as large as that of ^{38}Cl . Because of the low yield from the (n, γ) reaction and the very small probability for internal conversion, the effect which $^{38\text{m}}\text{Cl}$ may cause is extremely small. The product distribution for the 61 eV hot atom may very well be the same as the 527 eV hot atoms; thus, to try to distinguish between them would be very difficult.

D. Definitions and Criteria for Hot Reactions

In order to define a hot reaction, a comparison must be made to thermal reactions. Table II compares thermal to hot reactions.

TABLE II

COMPARISON OF INTRINSIC PROPERTIES OF
THERMAL VERSUS HOT REACTIONS*

<u>Property</u>	<u>Thermal</u>	<u>Hot</u>	<u>Experimental Criterion</u>
1. Multiplicity of paths	Generally only one path	Usually multiple paths	Nature of products
2. Collision efficiency	Low	High	Scavenger effects
3. Temperature dependence	Yes	Very slight	Temperature dependence of competitive reactions in mixture
4. Effect of chemically inert additives	None	Yes	Moderator effects

* taken from reference 7

The nature of the product formed is a very common way to distinguish hot and thermal reactions. Recalling Figure 1, thermal reactions will have in most cases only a single reaction path via an activated complex, which may be able to decompose to give several products. Hot reactions may have a number of different reaction pathways. This criterion can be misleading because both a thermal and a hot reaction can sometimes give the same products.

To eliminate the problems of distinguishing between thermal and hot atom reaction products, scavenger techniques are used. Thermal reactions have low collision efficiencies whereas hot atom reactions must occur in a few collisions so as to react in the appropriate energy region. Addition of a small amount (two to five mole percent) of a scavenger capable of reacting efficiently with the thermalized atom, eliminates thermal reaction products formed; this process, the scavenger reaction, distinguishes thermal from hot reaction products. The scavenger will not significantly affect hot reactions since a hot atom is unlikely to encounter it during the few collisions of its existence. Figure 3 shows an example of the scavenger reaction.³⁷ The percent of ^{128}I labelled organic products was plotted as a function of the concentration of I_2 scavenger following neutron irradiation of ethyl iodide. This result indicates that in the presence of small amounts of I_2 , the thermal reaction can be almost completely eliminated. The most common scavengers are bromine, iodine and oxygen.

Hot atom reactions are temperature independent whereas thermal reactions are temperature dependent. This criterion may be

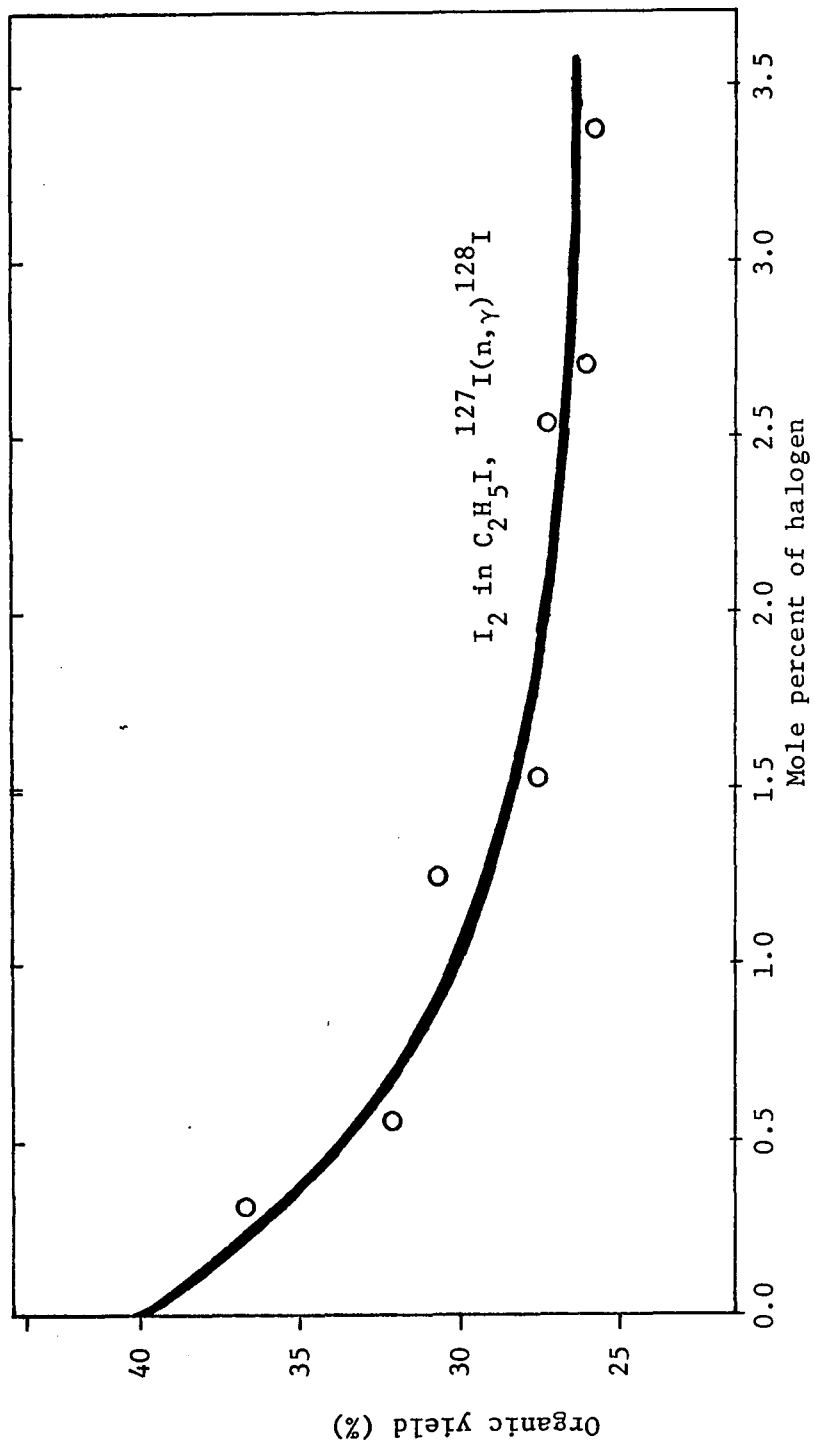


Figure 3. Effect of I_2 Scavenger on ^{128}I for I Substitution in Ethyl Iodine*
* taken from reference 37

misleading in distinguishing between the two because products of hot reactions may undergo temperature dependent secondary thermal reactions.

For gas phase systems, the use of chemically inert moderators has proven most useful. Addition of inert moderators, such as noble gases, will have no effect on the thermal energy distribution but will reduce the number of collisions of the hot atom in the reactive energy region, reducing the probability for the hot reaction to occur. Figure 4 shows the He moderation of recoil tritium in propane.³⁸

E. Cage Reactions

Frank and Rabinowitch³⁹ first introduced the cage reaction to account for a situation created in solution when two radicals or atoms are formed simultaneously in the same location. Due to the slowness of the diffusion process in liquid, the original partners can remain together for about 10^{-10} seconds and the probability of their mutual interaction is increased. In hot atom chemistry, a cage reaction is a sequence beginning with a collision in which the hot atom produces a radical that is trapped by the solvent in the same cage as the hot atom. The hot atom becomes thermalized by collision with the cage walls and then undergoes thermal combination with the radical. These "primary" cage processes are temperature independent, not affected by low concentrations of scavengers, and necessarily absent in the gas phase.⁴⁰

There are two types of immediate caged reactions which may

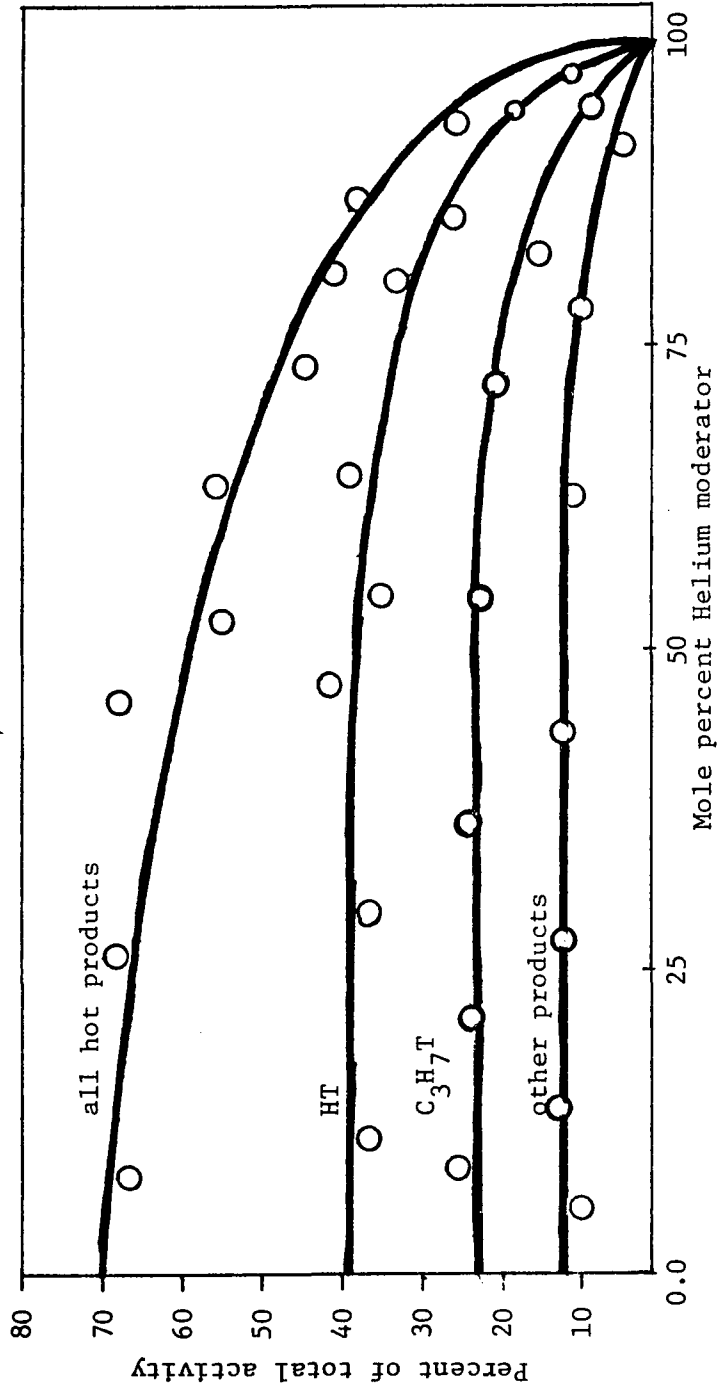
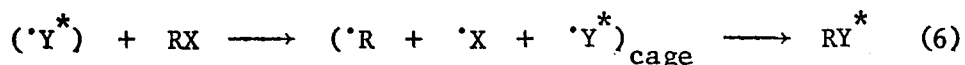


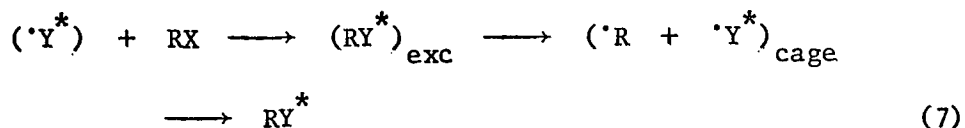
Figure 4. Effect of He Moderation of Recoil Tritium in Propane*

* taken from reference 38

occur.



This reaction will be called a cage recombination where hot atom Y strikes a molecule RX, which produces radicals trapped in a cage. The hot atom Y loses energy by collisions in the cage and later forms an energetic RY.



In this reaction, the primary step is a hot displacement process where hot atom Y strikes a molecule RX, which directly replaces X and forms a highly excited molecule. The excited (RY^*) breaks up and the resulting species are trapped in the cage, become thermalized by the solvent forming the cage, and eventually recombine to produce RY^* . Cage recombination models, rather than direct hot replacement models, have been considered by several authors as the basis for theories of recoil atom reactions in the condensed phase.

The distinction between cage and hot displacement reactions is difficult to establish. In hot displacement reactions, the product is formed within the time span of one bond vibration. This product will be formed in a highly excited state which must be stabilized by immediate collisional energy transfer. These collisions will take place with the walls of the molecules making up the cage. Whether the energetic fragmentation products according to the cage model become thermalized by the cage walls or whether a highly

excited state of a product becomes stabilized by collisions with the solvent wall, both processes can be considered as hot reactions; it is a difficult task to distinguish between them. Scavenger effects can provide only a distinction between hot reactions (both cage and hot displacement) and thermal or diffusive processes.

Frank-Rabinowitch caging has long been a central concept in condensed phase hot atom chemistry.⁴¹ Evidence that caging exists was derived in experiments by Rice and Willard,⁴² Richardson and Wolfgang.⁴³ Both groups of workers studied the influence of a continuous increase in density from the gas phase up to closely packed liquid or solid on the yields of major products. Figure 5 shows the Richardson and Wolfgang experiment where absolute yields of ^{18}F for H and ^{18}F for F substitution in CH_3F are measured as a function of densities from 0.0014 g-cm^{-3} (gas at 1.1 atmospheres) to 1.1 g-cm^{-3} . Both the CH_3^{18}F and the CH_2^{18}F yields show a sharp rise from the lowest gas densities, leveling off at about 0.2 g-cm^{-3} (50 to 100 atmospheres). This behavior is characteristic for collisional de-excitation of highly excited primary products. Above the critical density, a second rise is observed, which was attributed to cage effects. It is also indicated, on the basis of Figure 5, that caging becomes important only when mean intermolecular distances shrink to about half the diameter of the fluorine atom. The experiments also show that there is no temperature effect.

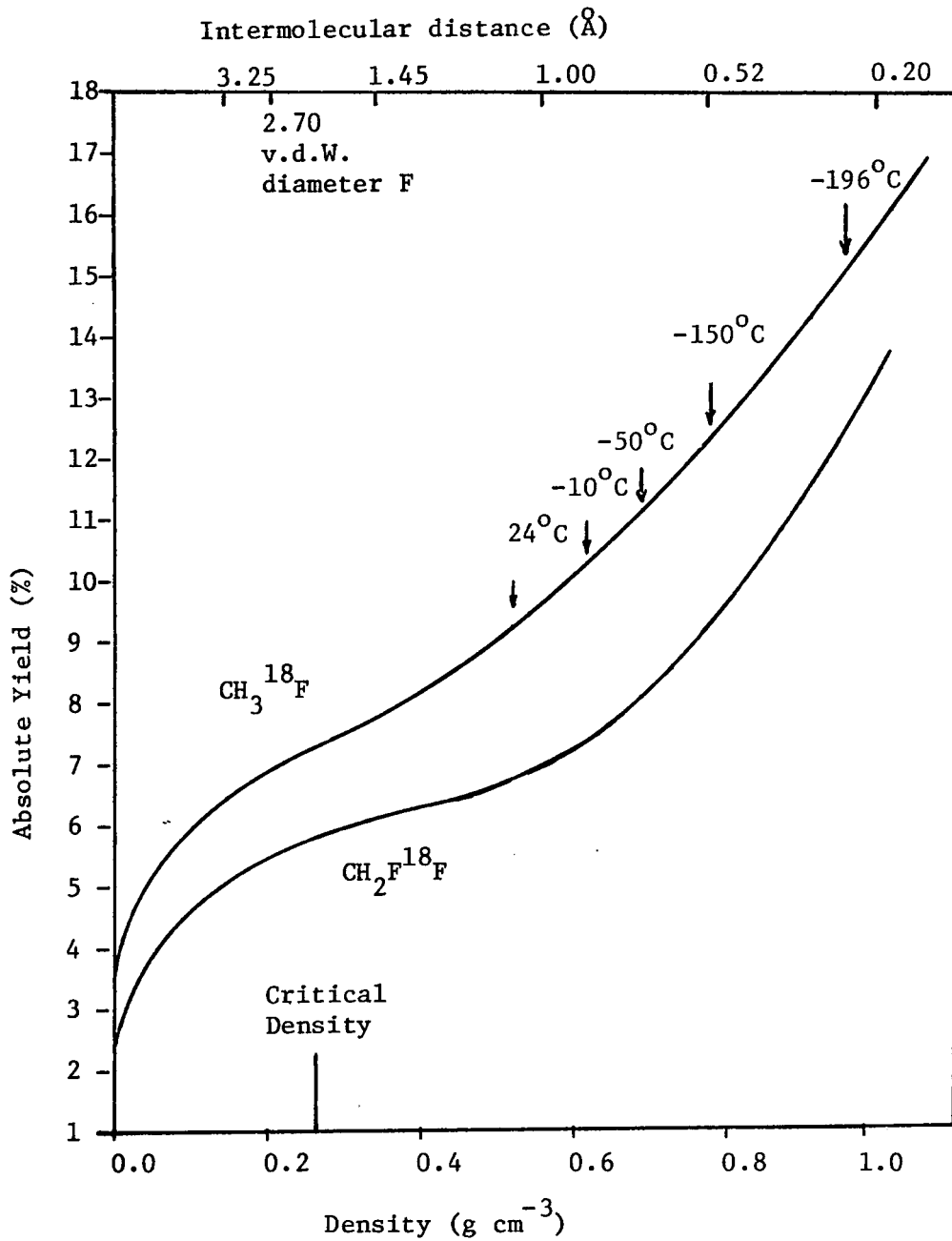


Figure 5. Richardson and Wolfgang, Absolute Yields of ^{18}F for H and ^{18}F for F Substitution in CH_3F Are Measured as a Function of Densities*

* taken from reference 43

F. Mechanisms in Hot Atom Chemistry

1. Billiard ball collision-epithermal collision

The model was first postulated by W. F. Libby⁴⁰ and later modified by Miller, Gryder and Dodson.⁴⁴ The term "billiard ball" came from the idea that the recoiling atoms acted as hard spheres when collisions occurred with neighboring molecules. The billiard ball collision hypothesis states that atoms recoiling with a few hundred eV of energy in liquids lose their energy by momentum transfer in elastic collisions with single atoms. A recoiling halogen atom is of considerably larger mass than hydrogen or carbon atoms in the organic molecule. Only collisions with another halogen atom in the halide molecule can result in a nearly complete transfer of momentum and energy in a single collision. Collisions with hydrogen, carbon atoms, and even methyl radicals will leave the recoiling atom with a considerable fraction of its energy after any single collision. The fractional energy loss per collision in such cases is

$$\frac{E_{\text{loss}}}{E_{\text{initial}}} = \frac{4 M M_1}{(M + M_1)^2} \cos \phi \quad (8)$$

where M and M_1 are the masses of the impinging atom and the struck atom, respectively, and ϕ is the angle between the paths of the atoms after collision.

A head-on collision between a hot halogen atom and a halogen bound to a molecule would lead to nearly complete transfer of

energy to the struck atom, thus projecting it into the medium. The de-energized impinging atom would remain in the solvent cage with the organic radical and would have a high probability of combining with the radical to form a new organic halide molecule. When this type of reaction occurs, the term "retention" is employed. If the collision were glancing, the energy transfer would not be complete, and the impinging atom would escape from the cage without undergoing combination with the organic radical. The same would be true if the hot halogen atom collides with a hydrogen or carbon in the molecule; therefore, hot halogen atoms would only be slowed down and escape from the solvent cage without chemical bond formation.

The above theory predicts that all recoil atoms which re-enter organic combinations must do so as the parent compound for one hundred percent retention. However, it was observed that dibromopropanes were formed from irradiation of propyl bromide. This led to a modification of the billiard ball model by Friedman and Libby⁴⁵ which now included epithermal collision. If recoil atoms have their energy reduced to the order of ten eV by successive collisions with hydrogen or carbon atoms, a new type of energy transfer becomes possible. It was postulated that in this energy region, the halogen atom may transfer energy to molecules as a whole in an inelastic collision, with rupture of one of the bonds of the molecule resulting from vibrational excitation. If a hydrogen bond were broken in such a process, the halogen atom would be in the cage with the radical formed and thus would have an opportunity to substitute

for the hydrogen in reforming a stable molecule. Reactions of this type have been termed "epithermal", in contrast to those occurring at higher energies.

2. Random fragmentation^{11,12}

When a halogen atom in a liquid phase molecule acquires several hundred eV of recoil energy, it starts moving rapidly and, after travelling less than a molecular diameter, encounters a solvent molecule. If this were an isolated molecule, the energetic atom would transfer momentum to it or to one of its atoms in an elastic collision and would continue on its way. In the liquid phase, this cannot happen because the struck molecule is backed and surrounded by a close-packed, sometimes intertwined wall of other molecules. The result is that the energy is dissipated by the breaking of bonds in a rather indiscriminate fashion in the immediate vicinity of the energetic atom. When the energy of the atom has been reduced below bond breaking energies, it will find itself in, or adjacent to, a pocket of organic radicals and inorganic atoms. Before the halogen atom has had an opportunity to diffuse in the system as a thermal atom, it may combine with an organic radical or inorganic atom after it has been moderated to an energy where combination is possible. Alternatively, it may enter stable combinations by a "thermal process", after diffusion in thermal equilibrium with the medium. In a pure alkyl halide, where the activation energy for all possible reactions of the halogen atom with the solvent is high, the thermal atom will nearly always combine with a radical or

atom which it produced while losing its recoil energy and which it encounters after a variable number of collisions with solvent molecules. Such thermal reactions are vulnerable to competition from low concentrations of impurities, such as olefins, and from added elemental halogen.

The relative numbers and specific types of organic and inorganic fragments formed by the recoil atom will depend on the chemical nature, density, crystal structure of the medium, the mass, and possibly the energy of the recoil atom. Thus the relative yields of products which the recoil atom forms will also depend on these factors. It may also depend on the activation energies which control the recoil atom's reactions with the stable molecules of the solvent molecule.

3. Impact⁷

The fact that collision efficiencies of hot atom reactions are high, but that no internally equilibrated reaction complex is formed, must necessarily mean that the point and direction of impact determine what reaction paths are possible. This was first recognized when it was noted that, in alkanes, carbon-hydrogen bonds were broken more readily than the weaker carbon-carbon bonds. Such an effect can be attributed simply to the greater exposure to attack of the more externally situated carbon-hydrogen bonds.

While the number of possible modes of attack of an atom are of course infinite, it is convenient to classify them into four broad classes illustrated in Figure 6. Attack on a central atom

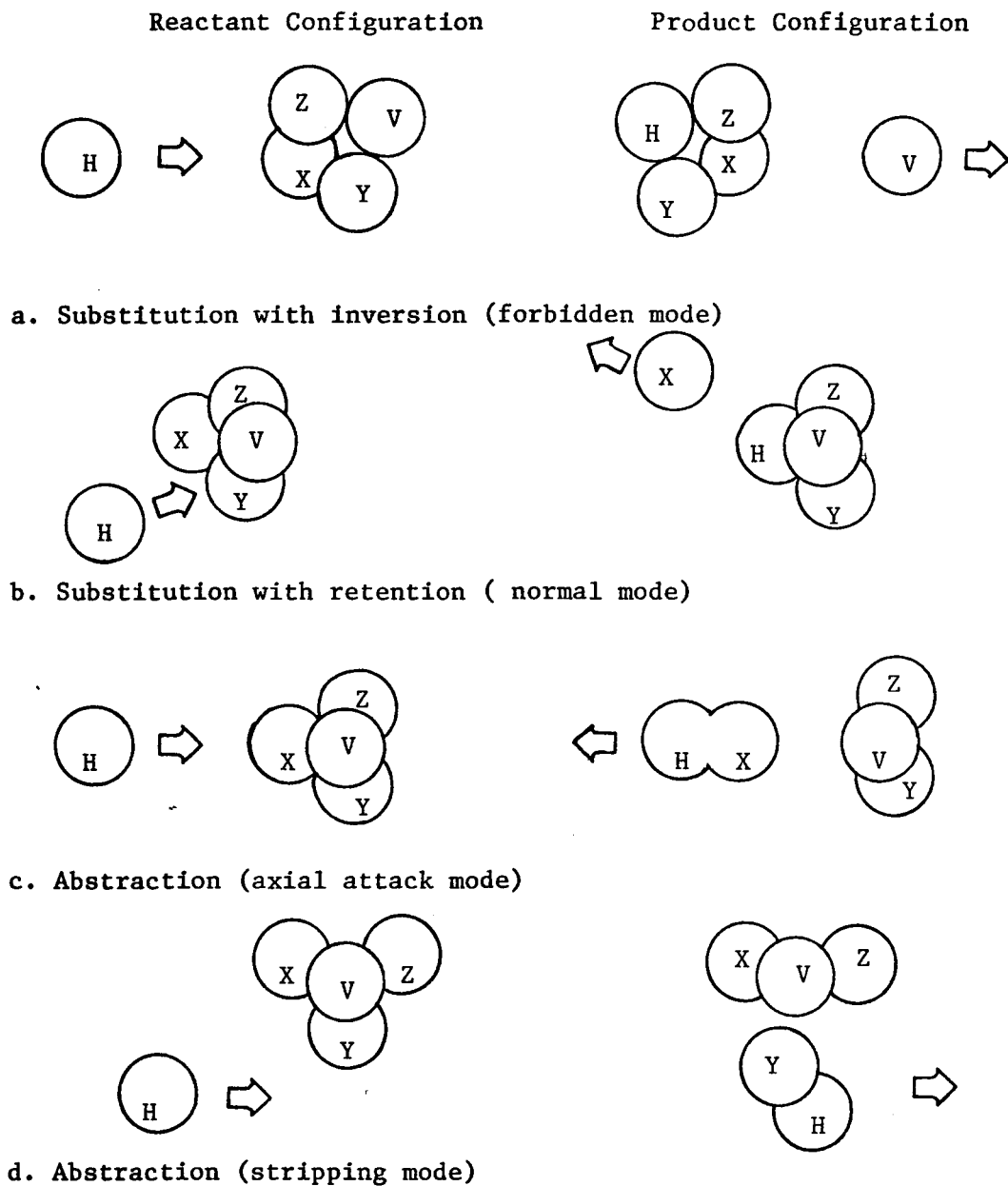


Figure 6. Modes of Reactions of Hot Hydrogen Atoms.

at a narrow angle (a) might be expected to lead to replacement of the atom on the other side of the central carbon with Walden inversion. If the attack is directed more towards one of the ligand atoms or groups, i.e., at a wider angle (B), the latter could be replaced without Walden inversion; although combination of the atom with the entity it is displacing in an abstraction-type reaction is also possible. Attack along the bond axis (C) can only result in abstraction of the atom struck. A glancing collision (D), can result in abstraction by a "stripping" mechanism. The considerations outlined above are steric factors, but there are also inertial factors to be considered which severely restrict certain of the possible reactions.

The importance of inertial effects is summarized in the "Golden Rule" of hot atom chemistry: "Hot atom reactions requiring nuclear motions which are slow relative to the time of collision tend to be forbidden."^{46,47} This is an extension of a general form of the Franck-Condon principle, requiring simply that concerted motions in any reaction must have similar relaxation times.

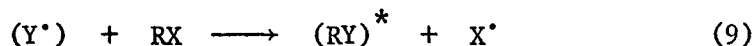
A striking example is the non-inversion of configuration on hydrogen replacement by hot hydrogen. Replacement with Walden inversion requires motion of the three groups that are not being replaced. Until this happens, no strong binding orbital can become available on the side of the carbon atom which the hot hydrogen is attacking. The characteristic vibration time of heavy groups (such as OH and CH₃) is greater than 10^{-14} seconds,⁴⁸ whereas the collisional time is 2.8×10^{-14} seconds, calculated for a 5 eV hydrogen

atom to transverse 5 \AA ; therefore, the hot hydrogen cannot become bound and will recoil and escape.

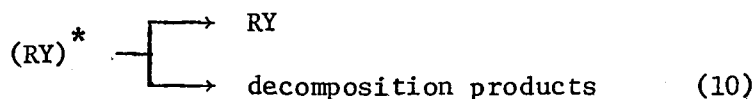
There is not any such restriction on hydrogen replacement by attack normal to the carbon-hydrogen bond. The displaced hydrogen atom can be expelled within the time of collision, making a binding orbital available to capture the incoming atom. Replacement by Walden inversion should also be permissible if the substituents are comparable to or lighter than the hot atom.

4. Direct replacement with collisional stabilization of caged complex model¹

Hot substitution in the gas phase is generally described as a direct replacement caused by a translationally hot atom.



On the basis of the impact model, this reaction should proceed with retention of configuration. The excited molecule $(RY)^{\bullet}$ can either decompose or become collisionally de-excited.



The excited molecules are known to have a wide spectrum of lifetimes, ranging from 10^{-13} to 10^{-8} seconds, and can thus already become stabilized in the gas phase over a wide pressure range. Early work by Rice and Willard,⁴² Richardson and Wolfgang,⁴³ and more recently Machulla and Stöcklin¹ has shown that the absolute yield for hot atom reactions increases with increasing density.

Stöcklin has also shown an increase in the retained substitution products in the pressure range from about 10^2 to 10^4 torr.

The different density dependence of the retained and inverted hot halogen for halogen substitution yield suggests that, in addition to the direct mechanism, another substitution mechanism must be operative and dominate in the liquid phase. At higher densities, particularly in the liquid phase, collision times are longer. The tightly packed molecules are kept together, and the time of interaction is longer. Solvation and efficient energy transfer may promote hot radical-molecule interactions which cannot occur in isolated gas phase collisions. A "caged complex" would explain the experimental results. This is to be distinguished from caged radical recombination by the numbers of radicals in the solvent cage. In caged recombination, which may lead to racemization, there are at least two radicals which have to recombine; in the "caged complex" mechanism, there is only one adduct formed from the hot atom and the substrate molecule. This "caged complex" is an electronically unstable molecule, which is held together by the surrounding molecules for a time sufficient for configurational changes.



Substitution processes leading both to retention and inversion of configuration would occur concomitantly, but racemization via a planar radical would not be possible.

G. Stereochemistry

The stereochemical course of a hot atom reaction can provide important information on the basic mechanism of the substitution process. Substitution reactions by hot tritium and hot halogen atoms at asymmetric carbon atoms occur predominately with retention of configuration. This can be seen for both tritium and halogens in Tables III and IV. In condensed phase systems, halogens are somewhat less stereospecific. The almost complete retention of configuration in gaseous systems (both tritium and halogens) has been explained by the impact model that assumes a direct replacement process on a time scale comparable to the molecular transit times for a hot atom (estimated at 10^{-14} to 10^{-13} seconds). Walden inversion should not be possible in hot atom reactions. The impact model is designed for recoil tritium in the gas phase and can also be extended for recoil halogens in the gas phase and tritium in the liquid phase. The somewhat smaller stereospecificity in condensed phase for recoil halogens has been attributed to radical-radical cage combination reactions. However, recoil halogens' molecular transit times may also be slow enough so that inversion is not a forbidden mode in terms of the impact model.

Stöcklin and coworkers¹ have studied the influence of a continuous increase in density from the gas to liquid phases and its effect on the stereochemical course of the reaction. Figures 7 and 8 show the ^3H for H and ^{38}Cl for Cl substitution in meso and d,l 1,2-dichloro-1,2-difluoroethane. It can be seen that the density

TABLE III

PREVIOUS RESULTS OF ^3H FOR H SUBSTITUTION AT
ASYMMETRIC CARBON ATOMS

Phase	System Studied	Retained Product	Inverted Product	Reference
Solid	Glucose	Glucose	Galactose	1 % 49
	L-Alanine	L-Alanine	D-Alanine	5 % 50
	d,1 DCB *	d,1 DCB	meso DCB	4.5% 2
Liquid	Glucose	Glucose	Galactose	10 % 50
	d,1 DCB	d,1 DCB	meso DCB	2.3% 2
	d,1 DCDFE **	d,1 DCDFE	meso DCDFE	19.6% 3
				20 % 1
Gas	meso DCDFE	meso DCDFE	d,1 DCDFE	6 % 3
				8 % 1
	D-2-Butanol	D-2-Butanol	L-2-Butanol	10 % 48
	L-2-Butanol	L-2-Butanol	D-2-Butanol	5 % 48
	d,1 DCB	d,1 DCB	meso DCB	7 % 2
	meso DCB	meso DCB	d,1 DCB	20 % 2
	d,1 DCDFE	d,1 DCDFE	meso DCDFE	2.4% 3
				4 % 1
				0.5% 3
				4 % 1

* DCB = 2,3-Dichlorobutane

** DCDFE = 1,2-Dichloro-1,2-difluoroethane

TABLE IV

PREVIOUS RESULTS OF RECOIL HALOGEN FOR HALOGEN
SUBSTITUTION AT ASYMMETRIC CARBON ATOMS

Phase	Recoil Halogen	System Studied	Retention Product	Inversion Product	Reference	
Solid	^{38}Cl	d,1 DCB ¹	d,1 DCB	meso DCB	50 %	5
	^{38}Cl	meso DCB	meso DCB	d,1 DCB	40 %	5
	^{38}Cl	(S)-CPC ²	(S)-CPC	(R)-CPC	50.8%	6
	^{18}F	d,1 DCB	threo FCB ³	erythro FCB	73.3%	4
	^{38}Cl	d,1 DCB	d,1 DCB	meso DCB	74 %	5
Liquid	^{38}Cl	meso DCB	meso DCB	d,1 DCB	74.4%	4
	^{38}Cl	(S)-CPC	(S)-CPC	(R)-CPC	70 %	5
	$^{34\text{m}}\text{Cl}$	(S)-CPC	(S)-CPC	(R)-CPC	52.7%	6
	$^{34\text{m}}\text{Cl}$	(R)-CPC	(R)-CPC	(S)-CPC	53 %	6
	$^{80\text{m}}\text{Br}$	d,1 DCB	threo BCB ⁴	erythro BCB	53.4%	6
	$^{80\text{m}}\text{Br}$	meso DCB	meso DCB	erythro BCB	92 %	51
	$^{80\text{m}}\text{Br}$	meso DCB	erythro BCB	threo BCB	58.3%	4
	$^{80\text{m}}\text{Br}$	meso DCB	erythro BCB	threo BCB	72 %	52
	^{82}Br	meso DCB	erythro BCB	threo BCB	95 %	51
	^{82}Br	meso DCB	erythro BCB	threo BCB	74 %	52
^{82}Br	meso DCB	erythro BCB	threo BCB	54 %	52	
^{82}Br	meso DCB	erythro BCB	threo BCB	46 %	52	

TABLE IV (CONTINUED)

Phase	Recoil Halogen	System Studied	Retention Product	Inversion Product	Reference
Liquid	82 Br	d,1 DCB	threo BCB 52 %	erythro BCB 48 %	52
	126 I	d,1 DCB	threo ICB ⁵ 54 %	erythro ICB 46 %	4
Gas	18 F	d,1 DCDFE ⁶	d,1 DCDFE 90 %	meso DCDFE 10 %	51
	18 F	meso DCDFE	meso DCDFE 90 %	d,1 DCDFE 10 %	53
	38 Cl	d,1 DCB	d,1 DCB 93 %	meso DCB 7 %	54
			93 %	7 %	51
	38 Cl	meso DCB	meso DCB 95 %	d,1 DCB 5 %	54
			95 %	5 %	51
	38 Cl	d,1 DCDFE	d,1 DCDFE 91 %	meso DCDFE 9 %	1
	38 Cl	meso DCDFE	meso DCDFE 92 %	d,1 DCDFE 8 %	1
	38 Cl	(S)-CPC	(S)-CPC 17.7%	(R)-CPC 82.3%	6
	38 Cl	(R)-CPC	(R)-CPC 20 %	(S)-CPC 80 %	6
	34 ^m Cl	(S)-CPC	(S)-CPC 18.8%	(R)-CPC 81.2%	6
	34 ^m Cl	(R)-CPC	(R)-CPC 21.3%	(S)-CPC 78.3%	6
	80 ^m Br	d,1 DCB	d,1 DCB 90 %	meso DCB 10 %	5
	80 Br	d,1 DCB	threo BCB 71 %	erythro BCB 29 %	55
	80 Br	meso DCB	erythro BCB 73 %	threo BCB 27 %	55

1. DCB = 2, 3-Dichlorobutane
2. (S)-CPC = 2(S)-Chloropropionyl Chloride
3. FCB = 2-Fluoro-3-Chlorobutane
4. BCB = 2-Bromo-3-Chlorobutane
5. ICB = 2-Iodo-3-Chlorobutane
6. DCDFE = 1,2-Dichloro-1,2-Difluoroethane

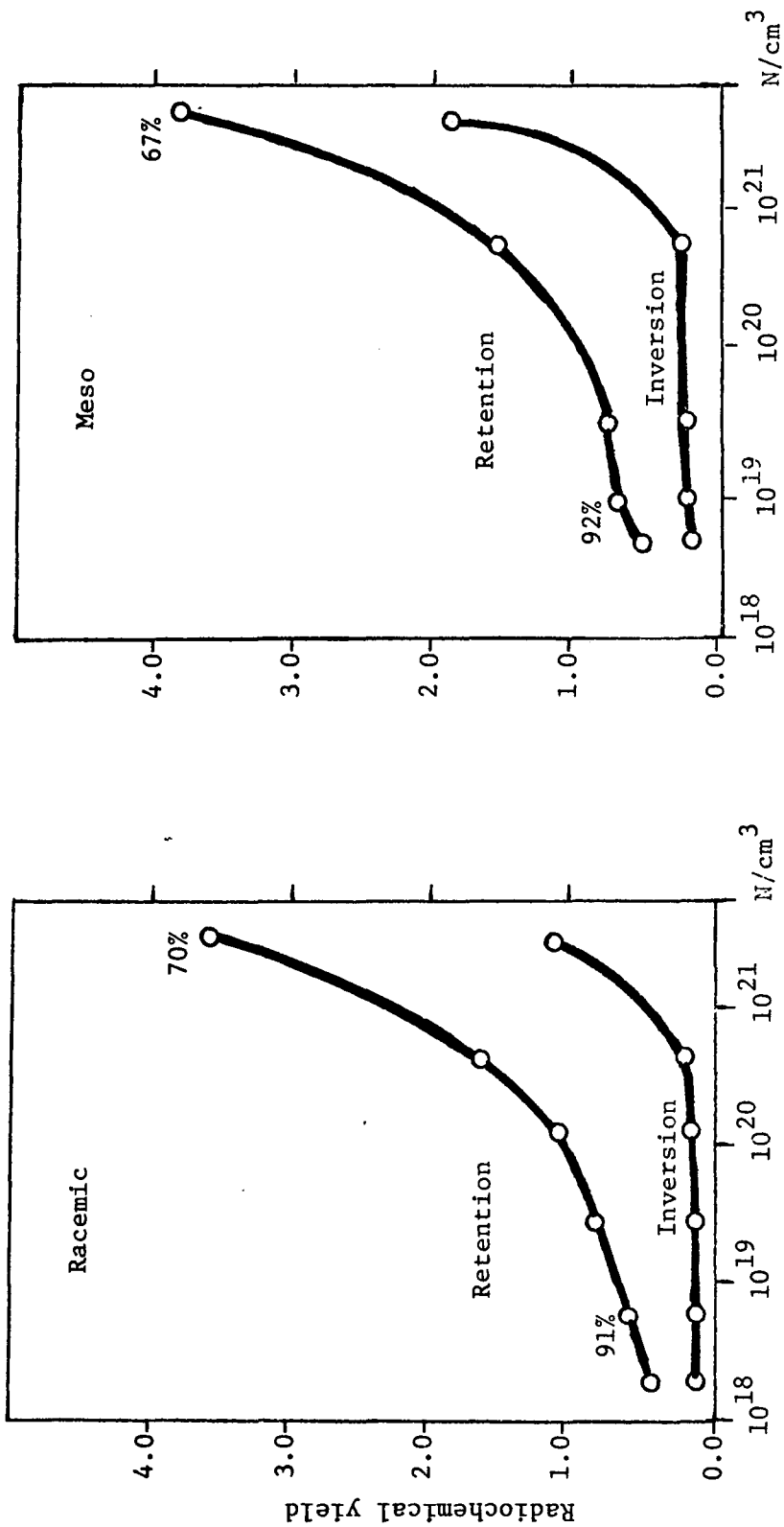


Figure 7. Density Effect in ³⁸Cl for Cl Substitution in Meso and Racemic 1,2-Dichloro-1,2-Difluoroethane*

* taken from reference 1

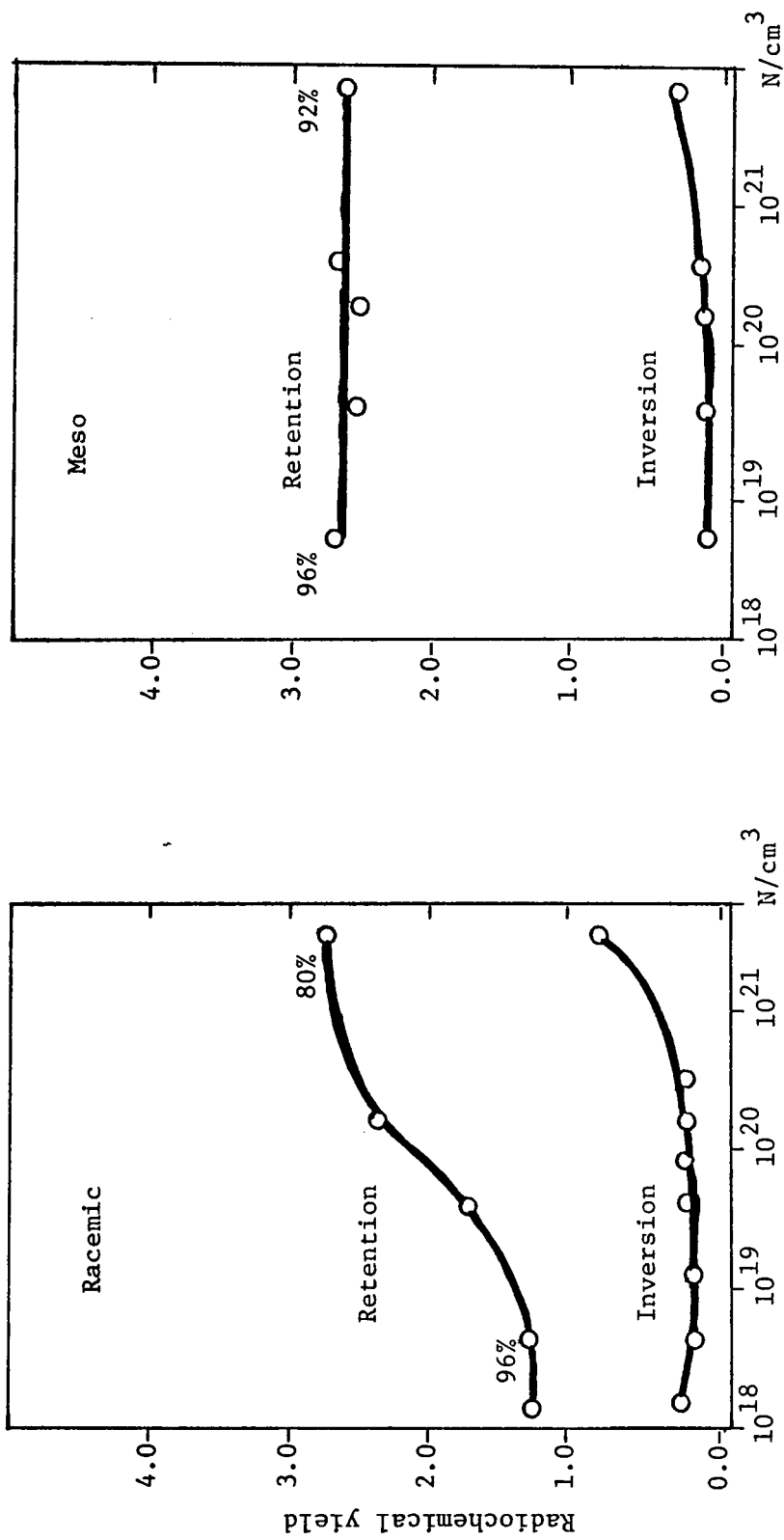


Figure 8. Density Effect in ³H for H Substitution in Meso and Racemic 1,2-Dichloro-1,2-Difluoroethane*

* taken from reference 1

dependence in ^3H for H substitution is very small when compared to ^{38}Cl for Cl. In the ^{38}Cl for Cl substitution reaction, both diastereomers act almost identically. The inverted product yield remains small over the entire pressure range and increases greatly when going to the liquid phase. The retained product shows the familiar increase in the gas phase because of enhanced collisional stabilization of the first excited product. The density dependence of the ^{38}Cl for Cl substitution yield resembles the trends observed by Richardson and Wolfgang⁴³ in the $^{18}\text{F}/\text{CH}_3\text{F}$ system. The decrease in stereospecificity may be due to radical caging. Tritium does not show this effect in the liquid phase because it may still have molecular transit times which are too fast for inversion, and its atoms may be too small to be trapped in a solvent cage.

H. Conformational Effect

It has been demonstrated by Stöcklin and coworkers⁴ that the stereochemical course of the ^{38}Cl for Cl substitution in meso and racemic 2,3-dichlorobutane can be influenced by solvent of various dielectric constants. Figure 9 shows that the stereochemical course of the substitution reaction can be varied over a wide range (from about 35% to 85% retention) by changing the nature and concentration of the solvent. The explanation of the above results is that the solvents are causing a change in the conformational population. Solvents with large dielectric value will affect the polar forms of the conformers where solvents of low dielectric value will affect the nonpolar forms of the conformers. In order to have a

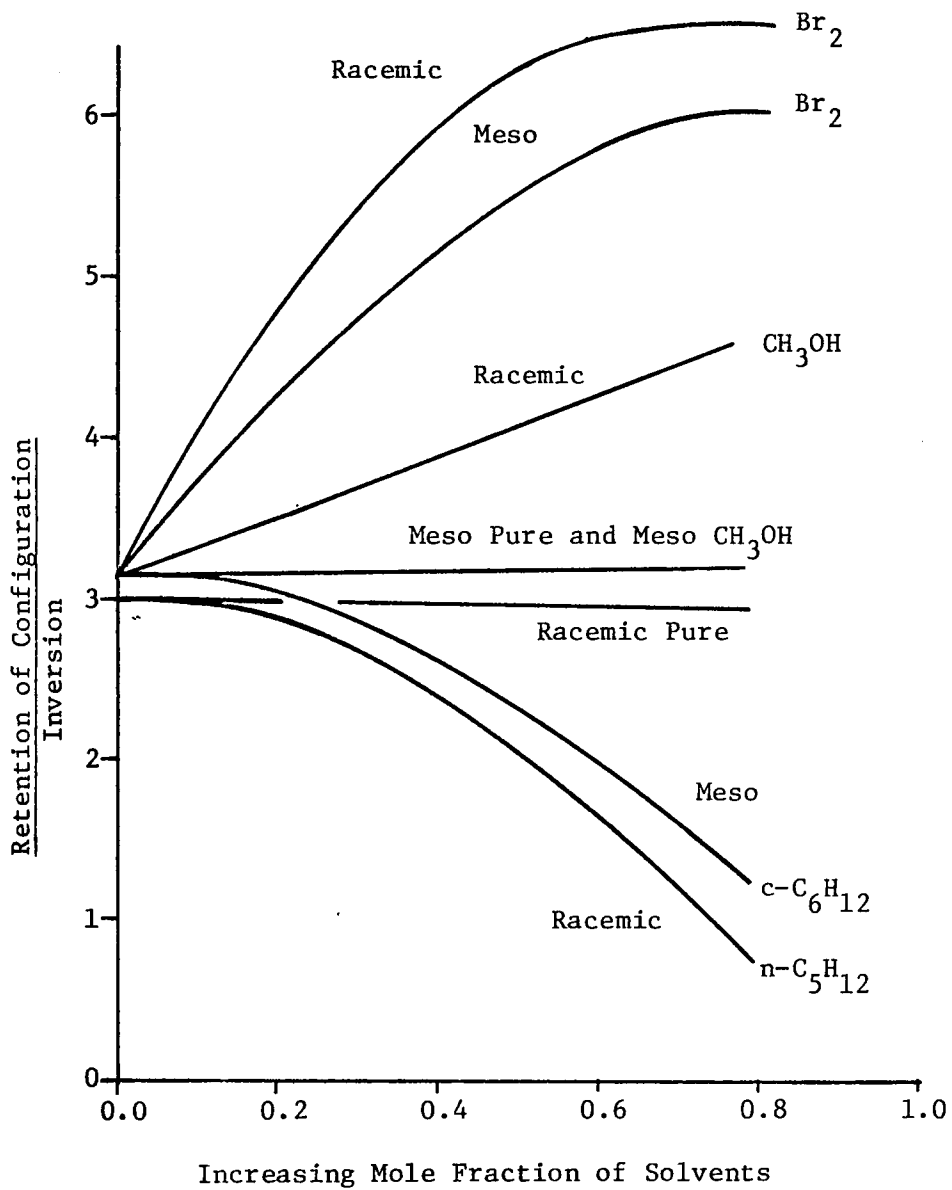


Figure 9. Solvent Effect on the Stereochemical Course of ³⁸Cl for Cl Substitution in 2,3-Dichlorobutanes*

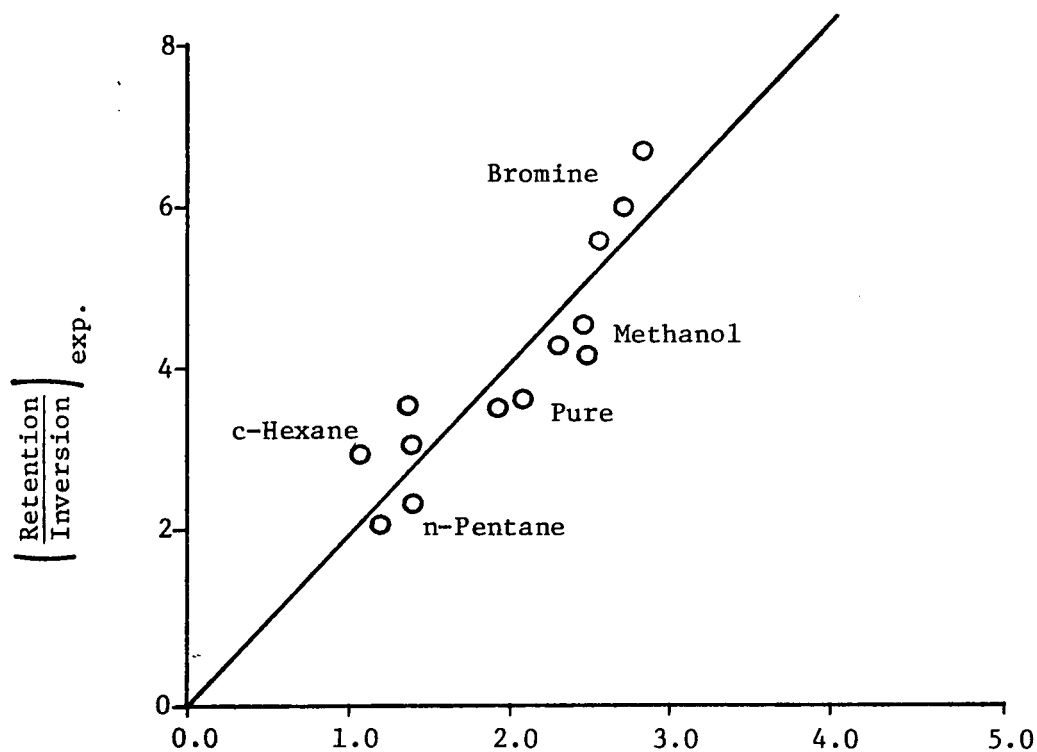
* taken from reference 4

complete understanding of possible conformational effects, a complete conformational analysis has to be carried out so that the conformational population is known for each solvent system.

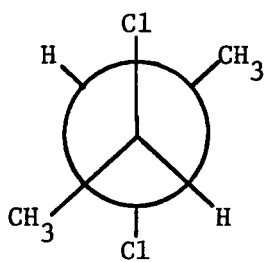
Stöcklin and coworkers have shown a correlation between the stereochemical course of the hot reaction (retention to inversion ratio) and the conformational population,⁴ assuming different reactive cross sections for substitution with retention (σ) and substitution with inversion (σ'), Figures 10 and 11. The conformational analysis of the above work was carried out with IR spectroscopy and, in the case of bromine, a theoretical calculation was performed. The reaction cross sections were determined by assuming certain values from kinetic evidence and employing a trial and error method for the other values. From Figures 10 and 11, Stöcklin has shown that the solvent effect is a conformational effect.

The conformational effect is very important because it could provide evidence for a one-step substitution mechanism. A change of conformation for the substrate molecule during impact and before bond formation seems unlikely since times for bond formation to take place (about 10^{-13} seconds) are faster than rotational changes (10^{-9} to 10^{-8} seconds). Conformational effects can also provide information on caged radicals or on intermediate substrate radicals which may become planar.

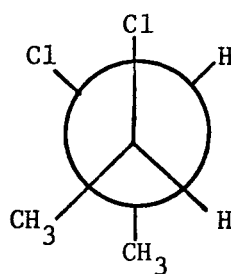
$$\frac{\text{Retention}}{\text{Inversion}} = \frac{\sigma_{\text{MT}}(\text{MT}) + \sigma_{\text{MG}}(\text{MG})}{\sigma'_{\text{MT}}(\text{MT}) + \sigma'_{\text{MG}}(\text{MG})}$$



$$\left(\frac{\text{Retention}}{\text{Inversion}} \right)_{\text{calc.}} = \frac{0.13 \text{ MT} + 4.50 \text{ MG}}{1.00 \text{ MT} + 0.26 \text{ MG}}$$



MT



MG

Figure 10. Conformational Effect on the Stereochemical Courses of ^{38}Cl for Cl Substitution in Meso 2,3-Dichlorobutane*

* taken from reference 70

$$\frac{\text{Retention}}{\text{Inversion}} = \frac{\sigma_{RT}(RT) + \sigma_{RG}(RG) + \sigma_{RG'}(RG')}{\sigma'_{RT}(RT) + \sigma'_{RG}(RG)}$$

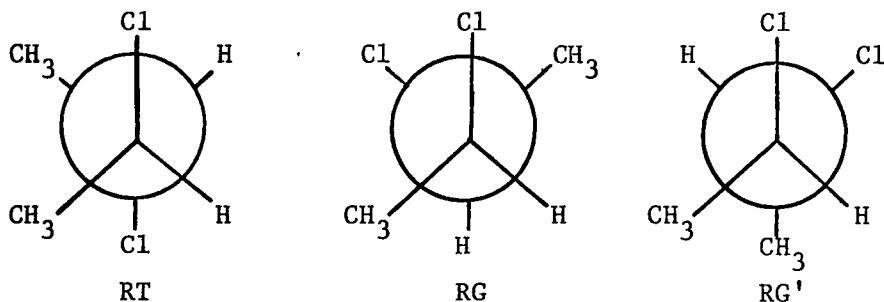
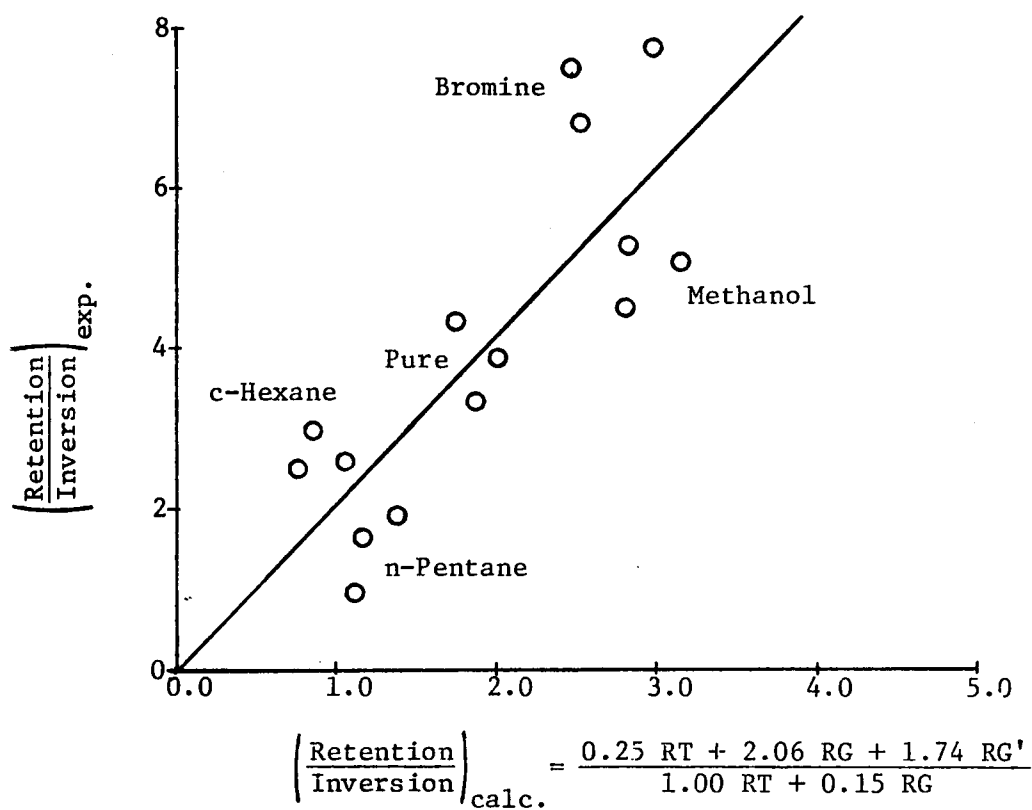


Figure 11. Conformational Effect on the Stereochemical Course of ³⁸Cl for Cl Substitution in Racemic 2,3-Dichlorobutane*

* taken from reference 70

VIII. EXPERIMENTAL

A. Purification of Starting Materials

1. Meso and racemic 1,2-dichloro-1,2-difluoroethane

A diastereomeric mixture of 1,2-dichloro-1,2-difluoroethane was obtained from Peninsular Chemical Research (PCR), Inc. The mixture was separated by gas chromatography into the meso and racemic forms; purity was one hundred percent for both forms. Table V shows the operating conditions of the column. The boiling points of the diastereomers are 59.4 °C for the meso (retention time 51 minutes) and 59.9 °C for the racemic (retention time 64 minutes).

2. Cis and trans-1,2-dichlorohexafluorocyclobutane

A cis/trans mixture of 1,2-dichlorohexafluorocyclobutane was obtained from Columbia Organic Chemicals Co., Inc. The mixture was separated by gas chromatography into the cis and trans forms. After a separation cycle on column A, a second separation was performed on column B to obtain 99 percent purity. The boiling points are 51.3 °C for the trans and 54 °C for the cis with retention times of 93 minutes and 98 minutes, using dibutyl phthalate column. The retention times were 75 minutes for trans and 85 minutes for cis, using an isoquinoline column. Table VI shows the operating conditions for both columns.

TABLE V

CONDITIONS EMPLOYED IN THE GAS CHROMATOGRAPHIC
SEPARATION OF DIASTEREOMERIC 1,2-DICHLORO-
1,2-DIFLUOROETHANE

Stationary phase	15% Bentone-38 and 10% Dow Corning Silicone Oil 200 (12,500 cs)
Solid support	Chromosorb W DMCS Treated Acid Wash
Particle size	60/80 mesh
Column length	15.24 M glass
Column diameter	6 mm I.D.
Carrier gas	Helium
Flow rate	150 cc per minute
Column temperature	75 °C
Detector temperature	150 °C
Injection port temperature	120 °C

TABLE VI

CONDITIONS EMPLOYED IN THE GAS CHROMATOGRAPHIC
SEPARATION OF THE GEOMETRIC ISOMERS OF
1,2-DICHLOROHEXAFLUOROCYCLOBUTANE

Stationary phase	30% Isoquinoline	30% Dibutyl Phthalate
Solid support	Chromosorb P-NAW	Chromosorb P-NAW
Particle size	60/80 mesh	60/80 mesh
Column length	15.24 M glass	22.86 M glass
Column diameter	6 mm I.D.	4 mm I.D.
Carrier gas	Helium	Helium
Flow rate	30 cc per minute	40 cc per minute
Column temperature	35 °C	70 °C
Detector temperature	120 °C	120 °C
Injection port temperature	100 °C	100 °C

3. Commercial materials

All solvents were either Certified A.C.S. Spectranalyzed from Fisher Scientific Co. or Spectro grade distilled in glass from Burdick and Jackson Laboratories, Inc. I_2 , purity greater than 98 percent, was obtained from Aldrich Chemical Company. Lithium fluoride, certified from Fisher Scientific Co., and all other materials were reagent grade.

B. Sample Preparation and Irradiation Procedure

1. 3H for H substitution in 1,2-dichloro-1,2-difluoroethane

Samples were prepared by placing ten milligrams of LiF (source of 3H), 2.5 milligrams of solid I_2 (thermal radical scavenger), 31.4 microliters of either meso or racemic 1,2-dichloro-1,2-difluoroethane and the appropriate amount of solvent into a quartz ampule. The ampule containing the solution was thoroughly degassed by the usual freeze-thaw technique and sealed. The sample was exposed to a neutron flux of $1.6 \times 10^{12} \text{ n-cm}^{-2}\text{-sec}^{-1}$ at room temperature at the Virginia Polytechnic Institute and State University nuclear reactor for fifteen minutes.

2. ^{38}Cl for Cl substitution in 1,2-dichloro-1,2-difluoroethane

Samples were prepared by placing 2.5 milligrams of solid I_2 , 31.4 microliters of either meso or racemic 1,2-dichloro-1,2-difluoroethane, and the appropriate amounts of solvent in a quartz

ampule. They were degassed using the same procedure and sealed under vacuum. The sample was then irradiated under the same conditions as above except that the irradiation time was only two minutes.

3. ^{38}Cl for Cl substitution in 1,2-dichlorohexafluorocyclobutane

Samples were prepared by placing 2.5 milligrams of solid I_2 , 10 microliters of either cis or trans 1,2-dichlorohexafluorocyclobutane, and the appropriate amount of solvent added. Degassing and irradiation were the same as above except that the time of irradiation was four minutes.

C. Gas Chromatographic Analysis of Neutron Irradiated Samples

1. ^{38}Cl for Cl and/or ^3H for H substitution in 1,2-dichloro-1,2-difluoroethane

The irradiated sample was frozen at liquid nitrogen temperature and the ampule opened. 100 microliters of an inactive carrier solution was added to the sample. The carrier solution contained two percent by volume of 1,2-dichloro-1,2-difluoroethane (both diastereomers) and 98 percent n-pentane. The sample was subsequently transferred to a vial and 150 microliters of n-pentane was added followed by the addition of 500 microliters of a ten percent solution of Na_2SO_3 and Na_2CO_3 . The inactive carrier was used as a mass indicator for the gas chromatographic separation of the two diastereomers. The pentane was used to increase the volume of the organic

layer. The salt solution was added to reduce any unreacted I_2 to I^- ions and to separate the labelled organic from the inorganic products. The lower inorganic layer was now removed, using a glass syringe, and the organic layer was dried with a few crystals of $CaCl_2$. After drying, the whole organic layer was injected into a Beckman GC-4 for separation. The Bentone-38 column used in the original separation of the diastereomers was employed for the radioactive gas chromatographic analysis at a temperature of $90^\circ C$ and a flow rate of 100 cc/minute.

2. ^{38}Cl for Cl substitution in 1,2-dichloro-hexafluorocyclobutane

The irradiated sample was frozen, opened and allowed to thaw. No inactive carriers were used because, at 99 percent purity of the substrate molecules, the one percent impurity consisting of the other diastereomers served as an inactive carrier and mass probe of both diastereomers could be detected.

Two hundred microliters of 10 percent Na_2SO_3 , Na_2CO_3 wash solution were added to the sample. The organic layer was separated, dried, and injected into the gas chromatograph for separation. The 30 percent dibutyl phthalate column was used at the same conditions as in the original sample purification procedure.

D. Radioactivity Measurements

1. ^{38}Cl for Cl substitution in 1,2-dichloro-1,2-difluoroethane and 1,2-dichloro-hexafluorocyclobutane

The Beckman GC-4 was equipped with a thermal conductivity detector. This, or any other gas chromatographic detector, could not distinguish between the active and inactive molecules. The only way to distinguish between them is to collect the effluent gas and measure the radioactivity in each compound eluted from the column. Gas chromatography separated the meso from the racemic forms, also the cis from trans. A three inch NaI detector in connection with an Ortec single channel analyzer was used to measure the ^{38}Cl activity. The effluent gas was collected on charcoal at one-minute intervals and then transported to the NaI detector where it was counted for one minute. The NaI detector was set up to detect the 1.45 gamma ray of ^{38}Cl , which has a half life of 37.2 minutes. The half life is checked by counting the same set of samples at two or three different time periods to test if the radioactivity decayed with a 37.2 minute half life.

2. ^3H for H substitution in 1,2-dichloro-1,2-difluoroethane

The gas chromatographic separation was carried out as described above. However, because of the difference between the ^{38}Cl (emission of a gamma ray) and ^3H (emission of a weak beta particle), different detection systems were used. In the tritium experiments

the charcoal trap was replaced with a cocktail for liquid scintillation detection in which the effluent from the gas chromatographic column was collected. The cocktail solution was prepared by dissolving 4 grams per liter of PPO (2,5-diphenyloxazole) and 0.2 grams per liter of POPOP (p-bis[2-(5-phenyloxazolyl)] benzene) in toluene. The samples did not have to be counted immediately after collection, and there was no need for a correction for the half life decay because of the long half life of ^3H (12.33 years). The beta radiation was counted with a Beckman LS-100 liquid scintillation system.

E. Determination of the Retention to Inversion Ratio

In any liquid phase hot atom reaction, there are many products which can form. Geissler and Willard⁵⁶ have shown that there are more than ten organic ^{38}Cl products formed by $^{37}\text{Cl}(n,\gamma)^{38}\text{Cl}$ activation of n-C₃H₇Cl in 99.9 percent n-pentane solution. Since this research is concerned with the stereochemical course of the hot atom reaction, only the ^{38}Cl activity obtained on the retained or inverted products were determined.

Since the retention time of meso 1,2-dichloro-1,2-difluoroethane is 51 minutes and 64 minutes for racemic 1,2-dichloro-1,2-difluoroethane and the half life of ^{38}Cl is 37.2 minutes, the ^{38}Cl will undergo almost two half life decays while the diastereomers are being separated. A correction for the activity must be made for the decay which occurs during the separation. Separation of the 1,2-dichlorohexafluorocyclobutane isomers requires about

110 minutes. Consequently, the irradiation time of this latter compound was extended to produce more activity because before the radioactivity can be counted, almost three half lives will have elapsed.

Radioactive decay is a first order reaction:

$$A = A_0 \exp(-kt) \quad (12)$$

where t is the time, k is the decay constant, A is the activity at time t and A_0 is the original activity. In this research, the activity is corrected back to the injection time of the sample in the gas chromatograph. In general the collection period starts at five minutes before the first peak and continues every minute through the tail of the second peak. The discontinuous collection is necessary in order to determine if there is overlapping of activity from other products formed in the hot reaction.

After each one-minute collection has been corrected for the ^{38}Cl decay, a plot is made of counts versus time, or sample number. This plot is shown in Figure 12 and will be called the radioactivity graph. The radioactivity graph may have many peaks because a number of ^{38}Cl labelled products are formed, but there will be two peaks which exactly match the mass peaks of the chromatogram assigned to the two isomers of 1,2-dichloro-1,2-difluoroethane. The total counts are determined for each peak by summing up the counts for each one-minute collection. The two peaks are labelled, indicating which one is the retained or inverted form. The retention to inversion ratio is determined by dividing the total inversion counts

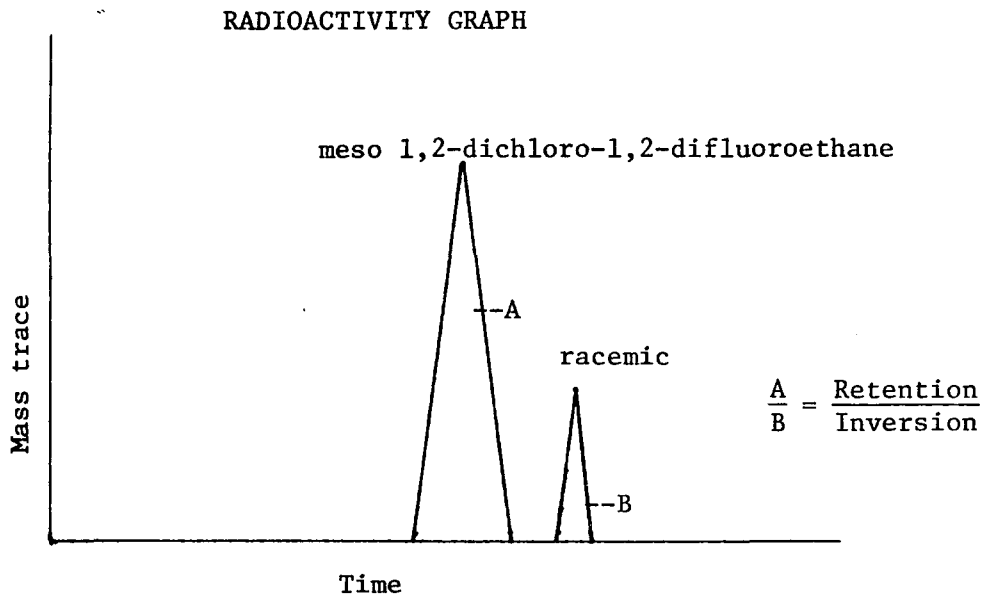
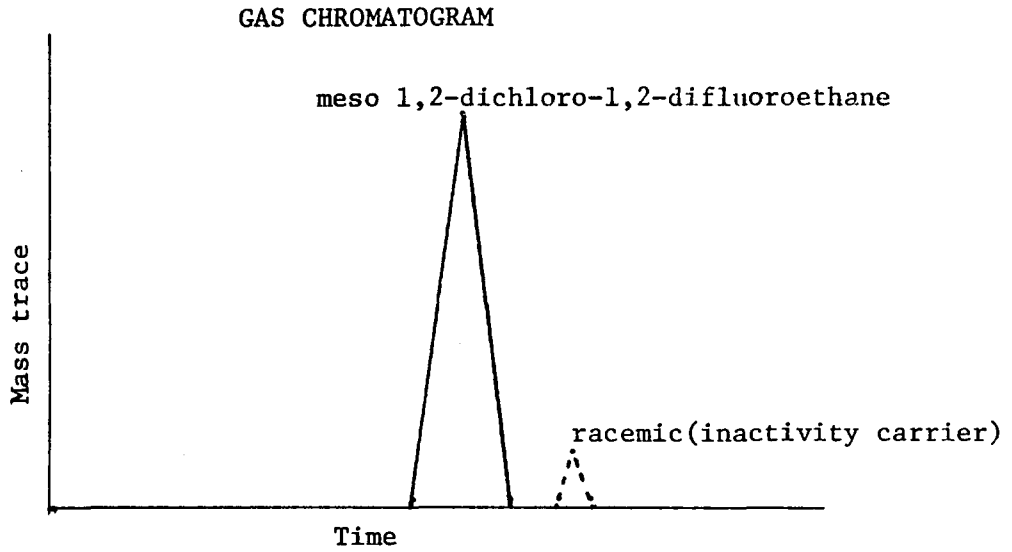


Figure 12. Comparison Between Gas Chromatogram and Radioactivity Graph

into the total retention counts. If the starting molecule is pure meso, then the ^{38}Cl labelled meso compound is the retained product. The racemic form obtained as a result of the hot reaction has to be formed under Walden inversion and is called the inverted product.

Some systems have a very complex radioactivity graph which will have more than two peaks. If an inactive carrier is not added, then it will be difficult to distinguish which peak is the inverted product. This was especially true for the 1,2-dichloro-1,2-difluoroethane system because of additional peaks which tail into or from the meso or racemic peaks. A computer program has been designed to simplify the radioactivity graph. This program will be presented in Appendix A.

F. Conformational Analysis

1. General principles

Consider a molecule equilibrating between two states A and B, if the population of the two states in any solvent (S) are n_a and n_b , one has

$$A = B \quad (13)$$

$$K = \frac{n_b}{n_a} = \exp\left(\frac{-\Delta G^S}{R T}\right) \quad (14)$$

$$n_a + n_b = 1 \quad (15)$$

where ΔG^S is the free-energy difference for the equilibrium in solvent S.⁵⁷

In any other solvent or in the vapor, an identical equation

holds. Since one may be concerned with differences between different solvents or between the vapor and any solvent,

$$\gamma\Delta G = \Delta G^V - \Delta G^S \quad (16)$$

one may replace $\gamma\Delta G$ by $\gamma\Delta E$, the energy difference between the liquid and gaseous states and therefore needs only to calculate the variation of $E_a - E_b$ with solvent.

There are two types of experiments which may be used to obtain conformational energies, static and dynamic methods. The static method will be discussed because it is the only method used.

In static experiments the time scale of the experimental technique is such that interconversion between conformers occurs during a single measurement and a single quantity (M) is measured. The value of this parameter is then the weighted average of the values in the various conformers.

$$M_{\text{observed}} = n_a M_a + n_b M_b \quad (17)$$

If the values of M_a and M_b are known, then the value of G , E or n_a , and n_b is given from one measurement of M . The two most common examples of this method are the measurement of molecular dipole moments⁵⁸ and room temperature NMR coupling constants.

In meso 1,2-dichloro-1,2-difluoroethane, the two gauche conformers are identical where the two gauche conformers are different in racemic 1,2-dichloro-1,2-difluoroethane. Figure 13 shows the most stable conformers of meso and racemic 1,2-dichloro-1,2-difluoroethane. In cis 1,2-dichlorohexafluorocyclobutane, the two conformers are identical where in trans 1,2-dichlorohexafluoro-

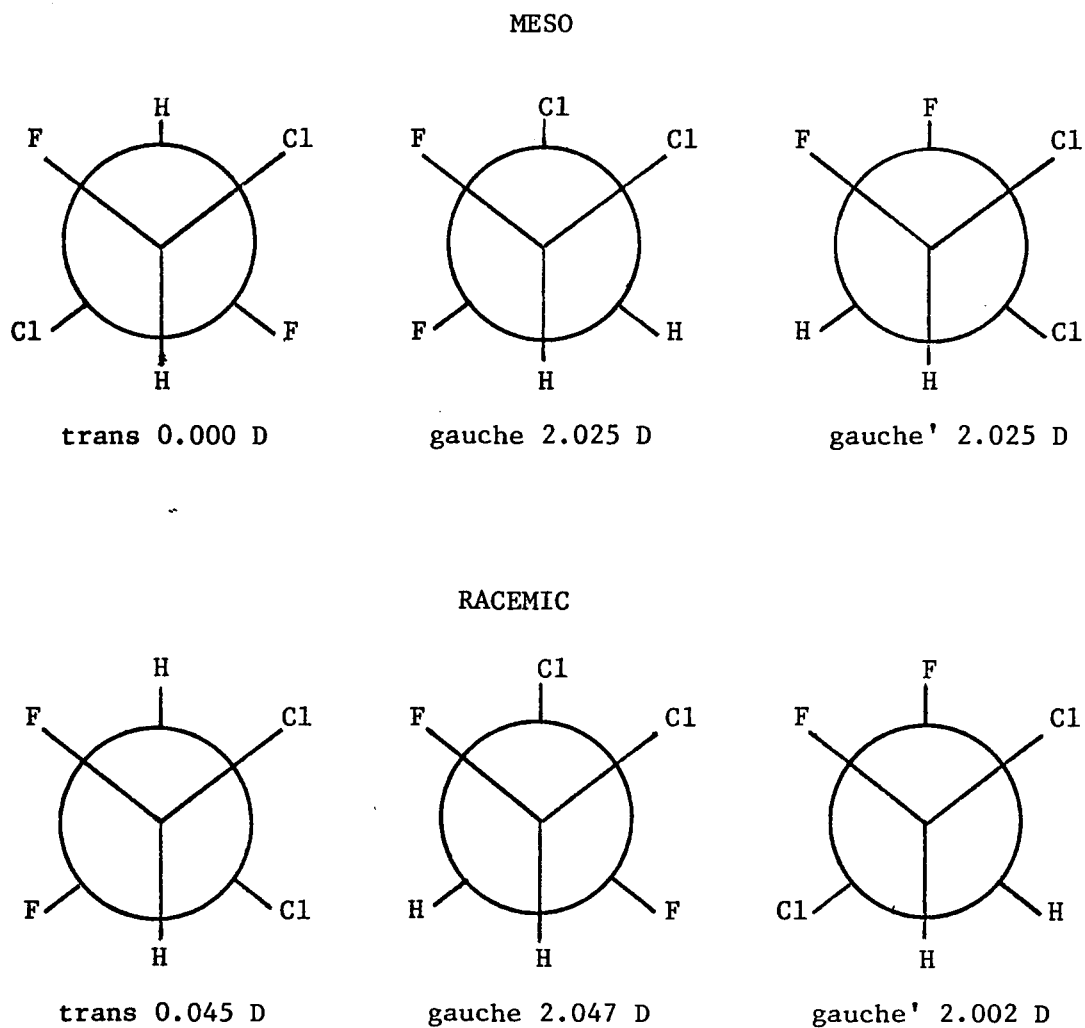


Figure 13. Most Stable Conformers of Meso and Racemic 1,2-Dichloro-1,2-Difluoroethane

cyclobutane there are two different conformers. Figure 14 shows the most stable conformers of cis and trans 1,2-dichlorohexafluorocyclobutane.

In the determination of conformational population by room temperature NMR or molecular dipole moments, the system becomes very difficult when there are three distinct conformers. Equations 15 and 17, which would be used for the calculation, must be expanded to include the third conformer. The new equations would now be

$$n_a + n_b + n_c = 1 \quad (18)$$

$$M_{\text{observed}} = n_a M_a + n_b M_b + n_c M_c \quad (19)$$

and there would be the problem of solving two equations with three unknowns. The only possible solution to the problem would be to find a third equation with the same unknowns or prove that two of the conformers are very similar and use Equations 15 and 17.

This research is concerned with the factors which control the stereochemical course of a hot atom reaction. In order to see if the conformational effect is one such factor, the conformational population must be known before the hot reaction. For molecules, meso 1,2-dichloro-1,2-difluoroethane, cis and trans 1,2-dichlorohexafluorocyclobutane, the determination of conformational population is a straightforward process using the general principles which have been previously stated. Since there are three distinct conformers for racemic 1,2-dichloro-1,2-difluoroethane, a different approach must be taken. It will be shown that the gauche conformers are very similar by the use of a computer program which calculates

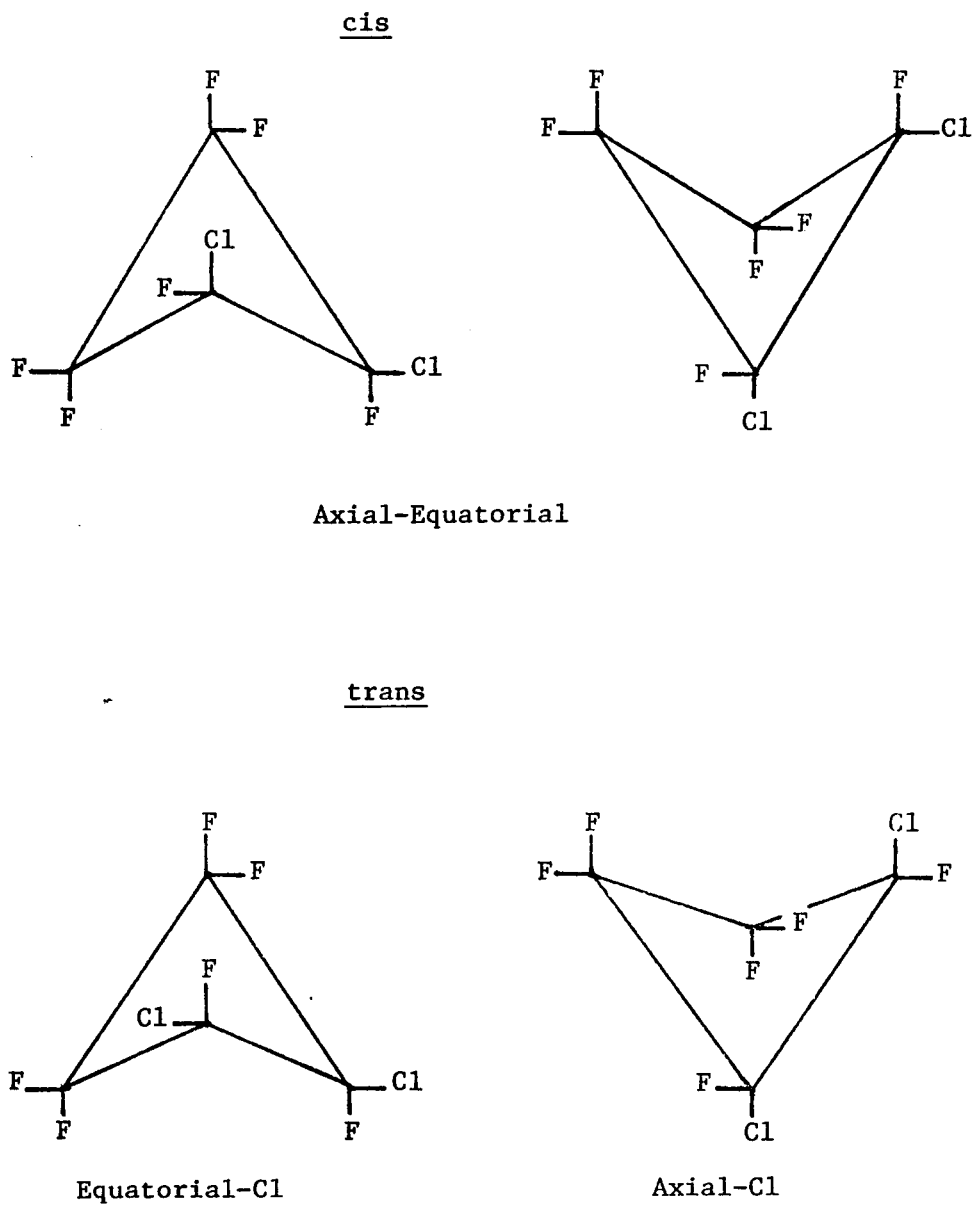


Figure 14. Most Stable Conformers of Cis and Trans
1,2-Dichlorohexafluorocyclobutane

individual conformer dipole moments. The program will be shown to be correct by predicting the molecular dipole moments for both meso and racemic. The calculated values of the molecular dipole moment will be compared to experimentally measured molecular dipole moments of the same molecule. Finally, the conformational population of racemic 1,2-dichloro-1,2-difluoroethane will be calculated on the basis that the two gauche conformers are the same and there is very little difference between the population of meso and racemic 1,2-dichloro-1,2-difluoroethane.

2. Experimental conditions for ^1H and ^{19}F NMR
of meso and racemic 1,2-dichloro-
1,2-difluoroethane

The ^1H spectra were measured at 100 MHz while the ^{19}F spectra were measured at 94 MHz; both were taken on a Jeol High Resolution NMR JNM-PS-100. The ^1H spectra were run on an internal lock with the strongest proton signal from the solvent as the lock. If the solvent did not provide a strong signal, tetramethylsilane was then used for the lock signal. The ^{19}F spectra were also run on an internal lock with hexafluorobenzene as the internal standard providing the lock signal. The sweep time was 250 seconds and a sweep width of 108 Hz was measured for both the ^1H and ^{19}F spectra. All solutions were ten percent by volume of either pure meso or racemic 1,2-dichloro-1,2-difluoroethane and 90 percent solvent. The pure samples of meso or racemic were run in a coaxial tube arrangement. The inner tube contained the pure material, and the outer volume contained CCl_4 and tetramethylsilane.

3. Experimental conditions for ^{19}F NMR of cis and trans 1,2-dichlorohexafluorocyclobutane

The ^{19}F spectra were measured at 94 MHz on a Jeol High Resolution NMR JNM-PS-100. The ^{19}F spectra were taken on internal lock with hexafluorobenzene providing the lock signal. The sweep time was 250 seconds and a sweep width of 1080 Hz for trans and 2700 Hz for cis. All solutions were ten percent by volume of trans 1,2-dichlorohexafluorocyclobutane and 90 percent additive.

G. Conformational Population of Meso 1,2-dichloro-1,2-difluoroethane

The conformational population is obtained by using room temperature ^1H NMR. The spin system for meso 1,2-dichloro-1,2-difluoroethane is an AA'XX' system and is analyzed using explicit relations for this system.⁵⁹ From the ^1H NMR spectra, $^3J_{\text{HH}}$, $^3J_{\text{FF}}$, $^3J_{\text{HF}}$, and $^2J_{\text{HF}}$ experimental coupling constants are found; also, ^{19}F NMR spectra gave the same results. Table VII compares ^1H NMR experimental coupling constants to ^{19}F NMR coupling constants. General Equation 17 now becomes

$$^3J_{\text{xx}}(\text{experimental}) = n_{\text{t}} ^3J_{\text{xx,trans}} + n_{\text{g}} ^3J_{\text{xx,gauche}} \quad (20)$$

where xx will be HH, HF and FF. The individual coupling constants for meso 1,2-dichloro-1,2-difluoroethane have been determined by R. J. Abraham.⁶⁰

In order to use Abraham's coupling constants, a series of

TABLE VII

COMPARISON BETWEEN ^1H AND ^{19}F NMR EXPERIMENTAL
COUPLING CONSTANTS (HERTZ) FOR MESO AND
RACEMIC 1,2-DICHLORO-1,2-DIFLUOROETHANE

<u>Additive</u>	^1H	^{19}F	$^3\text{J}_{\text{HH}}$	$^3\text{J}_{\text{FF}}$	$^2\text{J}_{\text{HF}}$	$^3\text{J}_{\text{HF}}$
90% pentane			4.7	29.0	49.2	5.6
10% meso			4.8	29.0	49.1	5.3
90% pentane			4.8	19.2	49.8	6.2
10% racemic			4.9	19.1	49.9	6.2
90% acetonitrile			2.7	20.8	48.0	9.0
10% racemic			2.8	20.7	48.1	9.0
90% methanol			3.4	20.5	48.4	8.3
10% racemic			3.1	20.0	48.0	8.6

experiments were performed to compare experimental coupling constants. In all cases, with the exception of one or two, agreement between the two sets of values are within 0.5 Hz, as is shown in Table VIII. Abraham had taken his spectra from a sample which contained both meso and racemic 1,2-dichloro-1,2-difluoroethane and had to use the ^{19}F spectra in order to analyze the ^1H spectra. Because both meso and racemic 1,2-dichloro-1,2-difluoroethane gave the same spectra, except for slight shifts in frequencies, the assignment of frequencies becomes very difficult and slight errors can be made. In this research, the ^1H NMR was taken of pure meso or racemic; the assignment of frequencies was not complicated by overlapping spectra due to the other compound.

Having established that there is good agreement between the two sets of spectra, Abraham's coupling constants were placed into Equation 17. Using Equations 15 and 17, the conformational population is obtained.

H. Determination of Experimental Molecular Dipole Moments for Meso and Racemic 1,2-dichloro-1,2-difluoroethane

The Higasi method⁶¹ was used for the determination of the molecular dipole moment in the dilute solution.

$$\mu = \beta \sqrt{de_{12}/df_2} \quad (21)$$

where β is a constant for the solvent, de_{12} is the change in dielectric constant of the solution with df_2 being the change in mole fraction.

TABLE VIII

COMPARISON BETWEEN THE EXPERIMENTAL COUPLING
CONSTANTS (HERTZ) OF R. J. ABRAHAM AND THIS
RESEARCH FOR MESO AND RACEMIC
1,2-DICHLORO-1,2-DIFLUOROETHANE*

<u>Additive</u>	$^3J_{HH}$	$^3J_{FF}$	$^2J_{HF}$	$^3J_{HF}$
pure meso	3.96	27.01	48.99	6.64
90% acetonitrile	3.5	26.0	48.7	7.3
90% pentane	2.9	24.0	48.4	8.6
90% cyclohexane	2.8	24.0	48.6	8.8
pure racemic	4.9	29.1	49.3	5.1
90% acetonitrile	4.7	29.0	49.2	5.6
90% pentane	4.65	29.0	48.7	5.3
90% cyclohexane	4.5	28.5	49.0	5.7
pure racemic	4.15	20.1	49.28	6.93
90% acetonitrile	4.1	20.1	49.0	7.3
90% pentane	2.9	20.6	48.05	8.85
90% cyclohexane	2.7	20.8	48.0	9.0
	5.2	19.1	49.9	6.5
	4.8	19.2	49.8	6.2
	4.95	19.0	49.4	6.35
	4.7	19.6	49.9	6.4

* taken from reference 60

$$\beta = \left[\frac{27 k T M}{4 N p_1 [e_1 + 2]^2} \right]^{1/2} \quad (22)$$

where k is the Boltzmann constant, T the absolute temperature, M the molecular weight of the solvent, N is Avogadro's number, p_1 is the density of the solvent and e_1 the dielectric constant of the solvent.

The change in dielectric constant for the solution was measured at 25 °C with a Dipolmeter by Kahl Scientific Instrument Corporation. Solution dielectric constants are measured by observing the change in capacitance as solution is introduced between the plates of a capacitor. The change is given by

$$C = (e_s - e_a) Cr \quad (23)$$

where e_s is the dielectric constant of the solution, e_a is the dielectric constant of air, and Cr is the "replaceable capacitance" of the cell.⁶²

The replaceable capacitance of the cell is determined by measuring the dielectric constant of several pure compounds.

$$Cr = \Delta e / \Delta s \quad (24)$$

where e is the difference between dielectric constants of two known compounds and s is the difference in scale readings for the two compounds. The replaceable capacitance of the cell is checked by measuring pure benzene and cyclohexane.

The solvent is cyclohexane because of its low dielectric constant (2.01) and the approximate percentage for the conformer population of meso is known from ^1H NMR experimental coupling

constants. The solution is very dilute (10^{-3} to 10^{-2} M) so that specific short-range dipole-dipole interactions would be very small. A ^1H NMR study shows that the conformational population in cyclohexane does not change in dilute solution, as is shown in Table XXII.

The change in dielectric behavior is now plotted as a function of mole fraction (Figure 15) and the slope of the curve is determined. Equation 21 now becomes

$$\mu = \beta \sqrt{\text{slope} \times Cr} \quad (25)$$

where β is 0.994 D for cyclohexane and Cr is 7.31×10^{-4} .

I. Experimental Conditions for the Determination of Molecular Dipole Moments

The molecular dipoles were experimentally determined by measuring the change in dielectric behavior for solutions at 25 °C with a Dipölmeter DM01 by Kahl Scientific Instrument Corporation. The measuring frequency for the instrument was 2 MHz.

Certified A.C.S Spectroanalyzed benzene and cyclohexane, by Fisher, were used as standards to calibrate the instrument. Cyclohexane was employed as the solvent for both 1,2-dichloro-1,2-difluoroethane and 1,2-dichlorohexafluorocyclobutane. Four solutions with varying concentrations for each isomer were measured in order to determine the molecular dipole moment.

J. Determination of Conformer Dipole Moments of Meso and Racemic 1,2-dichloro-1,2-difluoroethane

A computer program (Appendix B) was used to calculate the

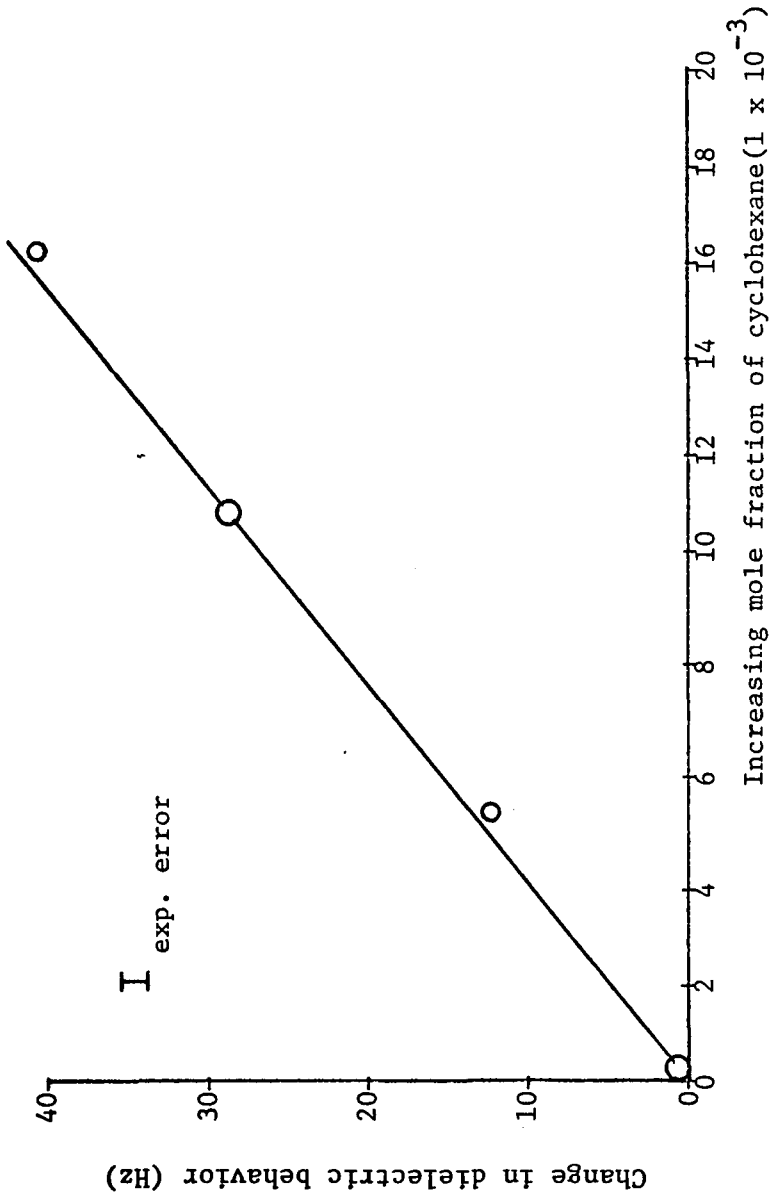


Figure 15. Change in Dielectric Behavior of a Solution of Meso 1,2-Dichloro-1,2-Difluoroethane and Cyclobutane as a Function of Mole Fraction

dipole moments⁶³ of the conformers of meso and racemic 1,2-dichloro-1,2-difluoroethane. Bond moments, bond lengths and bond angles had to be supplied and these values were obtained from molecules which had similar configuration to 1,2-dichloro-1,2-difluoroethane.

Table IX lists the values used in the computer program. The computer program was designed to sum the individual bond moments of the conformer as vectors in order to determine the dipole moment.

TABLE IX

STRUCTURAL PARAMETERS FOR THE CALCULATION OF
CONFORMER DIPOLE MOMENTS OF MESO AND RACEMIC
1,2-DICHLORO-1,2-DIFLUOROETHANE

	<u>C-C-Cl</u>	<u>C-C-F</u>	<u>C-C-H</u>	<u>C-C</u>	<u>F-C-Cl</u>
Bond Moments (D) ⁵⁸	1.70	1.63	0.4	0.0	
Bond Lengths (Å) ⁷⁵	1.73	1.34	1.10	1.53	
Bond Angles ⁷⁵	111.0°	109.5°	109.0°	0.0°	110.0°

IX. RESULTS

A. ^3H for H Substitution in Meso 1,2-dichloro-1,2-difluoroethane

The percentage of retained product obtained in the ^3H for H substitution in meso 1,2-dichloro-1,2-difluoroethane, in various concentrations of cyclohexane and n-propanol, are summarized in Table X.

The results indicate that the condensed phase hot ^3H for H substitution reaction has a high retention of configuration. These results are very similar to gas phase hot ^3H for H substitution reactions, therefore a single step mechanism would seem to explain the condensed phase reaction. Additional evidence to support a single step mechanism is that increases in the mole fraction of additive do not cause large changes in the percentage of retained product. Also, solvents with large dielectric constants (n-propanol, 20.1) should give a higher percentage of retained product than a solvent with a lower dielectric constant (cyclohexane, 2.01) which is not the case in this system. These results would be predicted by a single step mechanism, such as the impact model.

B. ^{38}Cl for Cl Substitution in 1,2-dichloro-hexafluorocyclobutane

The retention to inversion ratios obtained in the ^{38}Cl for Cl substitution is cis and trans 1,2-dichlorohexafluorocyclobutane,

TABLE X

PERCENT RETAINED PRODUCT IN ^3H FOR H SUBSTITUTION
IN MESO 1,2-DICHLORO-1,2-DIFLUOROETHANE

<u>Additive</u>	<u>Mole Fraction</u>	<u>% Retained Product</u>
cyclohexane	0.0	92 ± 10
	0.25	100 ± 10
	0.35	100 ± 10
	0.50	100 ± 10
	0.65	100 ± 10
	0.75	100 ± 10
	0.85	100 ± 10
	0.95	100 ± 10
	1.0	no activity
	n-propanol	0.0
0.25		89 ± 10
0.35		92 ± 10
0.50		92 ± 10
0.65		89 ± 10
0.75		85 ± 10
0.85		88.3 ± 10
0.95		81 ± 10
1.0		no activity

for various types of solvents at 0.8 mole fraction of additive, are summarized in Tables XI and XXII.

This system is of particular interest because ^{19}F NMR spectroscopy indicates that the conformational population of both cis and trans 1,2-dichlorohexafluorocyclobutane is independent of solvent. The results indicate that the retention to inversion ratio is not independent of solvent because perfluoroheptane and the pure compound differ drastically from hydrogen containing solvents. Methanol and cyclohexanone have retention to inversion ratios which are lower than the other hydrogen containing solvents because 1,2-dichlorohexafluorocyclobutane is immiscible with them. The results also indicate that hydrogen containing solvents show a very high retention to inversion ratio which is independent of the dielectric constant of the solvent.

C. ^{38}Cl for Cl Substitution in 1,2-dichloro-
1,2-difluoroethane

The retention to inversion ratios obtained in the ^{38}Cl for Cl substitution in meso and racemic 1,2-dichloro-1,2-difluoroethane, for various types of solvents at 0.5 and 0.8 mole fraction of additives are listed in increasing order of dielectric constant in Tables XIII and XIV.

The results indicate that increasing the dielectric constant causes increases in the retention to inversion ratio for both meso and racemic 1,2-dichloro-1,2-difluoroethane. These results are similar to those of Stöcklin, et. al., in the 1,2-dichlorobutane

TABLE XI

RETENTION/INVERSION RATIO IN ^{38}Cl FOR CL
SUBSTITUTION IN TRANS 1,2-DICHLORO-
HEXAFLUOROCYCLOBUTANE

<u>Additive</u>	<u>Mole Fraction</u>	<u>Retention/Inversion</u>
perfluoroheptane	0.8	2.6 ± 0.5
n-heptane	0.8	5.3 ± 0.5
cyclohexane	0.8	6.7 ± 0.5
n-pentanol	0.8	5.6 ± 0.5
methanol	0.8	4.4 ± 0.5
pure material	0.0	3.4 ± 0.5

TABLE XII

RETENTION/INVERSION RATIO IN ^{38}Cl FOR Cl
SUBSTITUTION IN CIS 1,2-DICHLORO-
HEXAFLUOROCYCLOBUTANE

<u>Additive</u>	<u>Mole Fraction</u>	<u>Retention/Inversion</u>
perfluoroheptane	0.8	1.2 \pm 0.5
n-heptane	0.8	7.1 \pm 0.5
cyclohexane	0.8	7.0 \pm 0.5
n-pentanol	0.8	5.6 \pm 0.5
cyclohexanone	0.8	4.6 \pm 0.5
pure material	0.0	3.2 \pm 0.5

TABLE XIII

³⁸CL FOR CL SUBSTITUTION IN MESO
1,2-DICHLORO-1,2-DIFLUOROETHANE

<u>Additive</u>	<u>Mole Fraction</u>	<u>Retention/Inversion</u>
perfluoroheptane	0.8	1.9 ± 0.5
n-pentane	0.5	2.9 ± 0.5
	0.8	2.4 ± 0.5
n-hexane	0.5	3.6 ± 0.5
	0.8	1.4 ± 0.5
n-heptane	0.5	4.0 ± 0.5
	0.8	2.9 ± 0.5
n-nonane	0.5	3.6 ± 0.5
	0.8	2.5 ± 0.5
n-decane	0.5	3.8 ± 0.5
	0.8	1.0 ± 0.5
cyclohexane	0.5	2.4 ± 0.5
	0.8	1.4 ± 0.5
bromine	0.5	5.25 ± 0.5
pure	0.0	2.5 ± 0.5
n-pentanol	0.5	4.0 ± 0.5
	0.8	2.8 ± 0.5
2-butanol	0.5	4.9 ± 0.5
n-butanol	0.5	3.15 ± 0.5
	0.8	2.2 ± 0.5
2-propanol	0.5	4.1 ± 0.5
cyclohexanone	0.5	5.0 ± 0.5
	0.8	3.8 ± 0.5
n-propanol	0.5	3.0 ± 0.5
	0.8	3.1 ± 0.5
ethanol	0.5	4.6 ± 0.5
	0.8	3.6 ± 0.5
methanol	0.5	4.5 ± 0.5
	0.8	3.6 ± 0.5
acetonitrile	0.5	2.6 ± 0.5
	0.8	2.2 ± 0.5

TABLE XIV

³⁸CL FOR CL SUBSTITUTION IN RACEMIC
1,2-DICHLORO-1,2-DIFLUOROETHANE

<u>Additive</u>	<u>Mole Fraction</u>	<u>Retention/Inversion</u>
perfluoroheptane	0.8	1.0 ± 0.5
n-pentane	0.5	2.7 ± 0.5
	0.8	2.0 ± 0.5
n-hexane	0.5	3.15 ± 0.5
	0.8	2.0 ± 0.5
n-heptane	0.5	2.8 ± 0.5
	0.8	1.8 ± 0.5
n-nonane	0.5	2.55 ± 0.5
	0.8	2.3 ± 0.5
n-decane	0.5	2.3 ± 0.5
	0.8	2.3 ± 0.5
cyclohexane	0.5	2.8 ± 0.5
	0.8	2.35 ± 0.5
bromine	0.5	5.3 ± 0.5
pure	0.0	2.15 ± 0.5
n-pentanol	0.5	3.0 ± 0.5
	0.8	3.1 ± 0.5
2-butanol	0.5	3.3 ± 0.5
n-butanol	0.5	2.8 ± 0.5
	0.8	3.2 ± 0.5
2-propanol	0.5	3.4 ± 0.5
cyclohexanone	0.5	2.8 ± 0.5
	0.8	2.9 ± 0.5
n-propanol	0.5	4.0 ± 0.5
	0.8	3.6 ± 0.5
ethanol	0.5	4.1 ± 0.5
	0.8	3.85 ± 0.5
methanol	0.5	3.6 ± 0.5
	0.8	3.4 ± 0.5
acetonitrile	0.5	2.5 ± 0.5
	0.8	2.0 ± 0.5

system. Within experimental error, alkanes behave very similar to each other and increasing the length of the carbon chain does not affect the course of the hot reaction. Bromine, which has a dielectric constant of 3.0, gives a very high retention to inversion ratio whereas acetonitrile with a high dielectric constant of 35.9 gives a low retention to inversion ratio. Alcohols, cyclohexane and cyclohexanone follow the general trend of the dielectric constant. Perfluoroheptane gives an unusually low value for the retention to inversion ratio; this is similar to the 1,2-dichlorohexafluorocyclobutane system.

D. Calculation of Conformer Dipole Moments
for Meso and Racemic 1,2-dichloro-
1,2-difluoroethane

In order to use the experimental molecular dipole moments of meso and racemic 1,2-dichloro-1,2-difluoroethane, the conformer dipole moments for each molecule had to be calculated using the computer program. Figure 13 shows the Newman projections of the conformers for meso and racemic 1,2-dichloro-1,2-difluoroethane along with their dipole moments. Two gauche conformers of the meso molecule have to be equal and the trans conformer has to be zero from the geometry of the system and is confirmed in the calculated values. The racemic values are very similar to the meso which indicates that the conformational population of the meso and racemic 1,2-dichloro-1,2-difluoroethane are approximately equal.

E. Experimental Molecular Dipole Moments

1. Meso and racemic 1,2-dichloro-
1,2-difluoroethane

Table XV lists the experimental molecular dipole moments for both diastereomers of 1,2-dichloro-1,2-difluoroethane. The experimental molecular dipole moments are determined using cyclohexane as a standard. The results indicate that the conformational populations for meso and racemic 1,2-dichloro-1,2-difluoroethane are equal.

From the equation

$$\mu_{\text{exp}}^2 = n_1 \mu_{\text{trans}}^2 + n_2 \mu_{\text{gauche}}^2 \quad (26)$$

a check can be made on the calculated individual dipole moments for each conformer. The experimental molecular dipole moment is 1.3 D. From ^1H NMR, n_1 and n_2 are known in cyclohexane along with μ_{trans} and μ_{gauche} from the computer program. When these values are placed into the above equation, as is shown in Table XVI, the experimental molecular dipole and the calculated molecular dipole are within 0.1 D. This shows that the individual conformer dipoles are correct for the meso and the geometry which is employed in the computer program is correct. Since the difference between the meso and racemic is only the position of one atom the same geometry is used to calculate the individual dipoles of racemic 1,2-dichloro-1,2-difluoroethane. Again using the above equation for a check on the racemic, the two values are within 0.1 D therefore the two gauche conformers of racemic are similar enough to be treated as one.

TABLE XV

EXPERIMENTAL MOLECULAR DIPOLE MOMENTS OF MESO
AND RACEMIC 1,2-DICHLORO-1,2-DIFLUOROETHANE
(CYCLOHEXANE WAS USED AS STANDARD)

	<u>Dipole Moment (Debye)</u>
Meso 1,2-dichloro-1,2-difluoroethane	1.30 D
Racemic 1,2-dichloro-1,2-difluoroethane	1.31 D

TABLE XVI

COMPARISON OF CALCULATED TO EXPERIMENTAL MOLECULAR
DIPOLE MOMENTS OF MESO AND RACEMIC 1,2-DICHLORO-
1,2-DIFLUOROETHANE IN CYCLOHEXANE

	<u>Meso</u>	
(1.3) ² experimentally determined	= 0.57 determined from ¹ H NMR	+ 0.43 determined (μ) ² gauche from ¹ H NMR
μ _{trans}	= 0.00 D calculated computer program	μ _{gauche} = 2.025 D calculated computer program
(1.33) ² calculated	= (0.57)(0.00) ² + (0.43)(2.025) ²	
	<u>Racemic</u>	
(1.31) ² experimentally determined	= 0.53 determined from ¹ H NMR	+ 0.47 determined (μ ² gauche + μ ² gauche')/2 from ¹ H NMR
μ _{trans}	= 0.045 D calculated computer program	μ _{gauche} ' = 2.002 D calculated computer program
	μ _{gauche} = 2.047 D calculated computer program	
(1.39) ² calculated	= (0.53)(0.045) ² + (0.47)(4.099)	

2. Cis and trans 1,2-dichlorohexafluorocyclobutane

Table XVII lists the experimental molecular dipole moments for both geometric isomers of 1,2-dichlorohexafluorocyclobutane. Again, the experimental molecular dipole moments are determined using cyclohexane as a standard. The results indicate that the two geometric isomers are very similar and their conformational population are approximately equal.

F. Conformational Population of Meso 1,2-dichloro-1,2-difluoroethane

Table XVIII lists the percentages of conformers for meso 1,2-dichloro-1,2-difluoroethane, for various types of solvents at 90 percent additive. The percentages of conformers are obtained from ^1H NMR by using experimental coupling constants. The additives are listed in increasing order of dielectric constant. The results indicate that there is a correlation between the percentage of conformer and dielectric constant. Table XIX lists the experimental coupling constants which are used to obtain the percentages of conformers. Three of the four experimental coupling constants are used to obtain the percentages of meso conformers. The $^2\text{J}_{\text{HF}}$ experimental coupling constant is not used because it is insensitive to changes in the nature of the solvents.

G. Conformational Population of Racemic 1,2-dichloro-1,2-difluoroethane

Table XX lists the percentages for racemic 1,2-dichloro-

TABLE XVII

EXPERIMENTAL MOLECULAR DIPOLE MOMENTS OF CIS AND
TRANS 1,2-DICHLOROHEXAFLUOROCYCLOBUTANE

	<u>Dipole Moment</u>
<u>Cis</u> 1,2-dichlorohexafluorocyclobutane	No deviation from cyclohexane could be observed.
<u>Trans</u> 1,2-dichlorohexafluorocyclobutane	No deviation from cyclohexane could be observed.

TABLE XVIII

CONFORMER POPULATION FOR MESO 1,2-DICHLORO-
1,2-DIFLUOROETHANE

<u>Additive</u>	<u>% Trans</u>	<u>% Gauche</u>
90% perfluoroheptane	57.1	42.9
90% n-pentane	54.3	45.7
90% n-hexane	54.3	45.7
90% n-heptane	54.6	45.4
90% n-nonane	54.6	45.4
90% n-decane	55.6	46.4
90% cyclohexane	56.0	44.0
90% bromine	49.0	51.0
pure material	42.0	58.0
90% n-pentanol	42.0	58.0
90% 2-butanol	39.7	60.3
90% n-butanol	41.0	59.0
90% 2-propanol	38.8	61.2
90% cyclohexanone	34.0	66.0
90% n-propanol	40.0	60.0
90% ethanol	38.0	62.0
90% methanol	37.0	63.0
90% acetonitrile	31.7	68.3

TABLE XIX

EXPERIMENTAL COUPLING CONSTANTS (HERTZ) FOR MESO
1,2-DICHLORO-1,2-DIFLUOROETHANE

<u>Additive</u>	<u>$^3J_{HH}$</u>	<u>$^3J_{FF}$</u>	<u>$^2J_{HF}$</u>	<u>$^3J_{HF}$</u>
90% perfluoroheptane	5.0	29.7	49.6	5.4
90% n-pentane	4.7	29.0	49.2	5.6
90% n-hexane	4.8	29.0	49.0	5.4
90% n-heptane	4.6	29.1	49.0	5.5
90% n-nonane	4.7	28.9	49.1	5.6
90% n-decane	4.8	29.1	49.1	5.4
90% cyclohexane	4.9	29.3	49.2	5.3
90% bromine	4.2	27.9	48.9	6.2
pure material	3.5	26.0	48.7	7.3
90% n-pentanol	3.7	26.4	48.9	7.2
90% 2-butanol	3.6	26.0	48.3	7.9
90% n-butanol	3.6	26.1	49.0	7.2
90% 2-propanol	3.4	25.5	48.8	7.7
90% cyclohexanone	2.9	24.6	48.4	8.7
90% n-propanol	3.5	25.9	48.9	7.7
90% ethanol	3.4	25.4	48.8	7.8
90% methanol	3.3	24.8	49.0	7.6
90% acetonitrile	2.8	24.0	48.6	8.8

TABLE XX

CONFORMER POPULATION FOR RACEMIC 1,2-DICHLORO-
1,2-DIFLUOROETHANE

<u>Additive</u>	<u>% Trans</u>	<u>% Gauche</u>
90% perfluoroheptane	55.5	44.5
90% n-pentane	54.3	45.7
90% n-hexane	56.2	43.8
90% n-heptane	56.8	43.2
90% n-nonane	54.3	45.7
90% n-decane	55.5	44.5
90% cyclohexane	53.1	46.9
90% bromine	43.2	56.8
pure material	45.7	54.3
90% n-pentanol	40.7	59.3
90% 2-butanol	43.2	56.8
90% n-butanol	42.0	58.0
90% 2-propanol	43.2	56.8
90% cyclohexanone	29.6	70.4
90% n-propanol	38.2	61.8
90% ethanol	34.6	65.4
90% methanol	37.0	63.0
90% acetonitrile	28.4	71.6

1,2-difluoroethane, for various types of solvents at 90 percent additive. The percentages of conformer are obtained from ^1H NMR by using $^3\text{J}_{\text{HH}}$ experimental coupling constants. The additives are listed in increasing order of dielectric constant. The results indicate again that there is a correlation between the percentage of conformer and dielectric constant. Table XXI lists the experimental coupling constants but only the $^3\text{J}_{\text{HH}}$ coupling constant is used to determine the percentage of conformer.

Since the dipole moment work proves that the two gauche conformers are very similar, Equations 15 and 17 are used for the calculation of conformational population. In the meso system, the conformational population was determined from three different sets of experimental coupling constant data. In the racemic system, only $^3\text{J}_{\text{HH}}$ coupling constant of the meso from Abraham's work can be employed. Coupling constants for the racemic system are not found in the literature because the two gauche conformers are always treated as distinct species.

The $^3\text{J}_{\text{HH}(\text{trans})}$ and $^3\text{J}_{\text{HH}(\text{gauche})}$ coupling constants of meso 1,2-dichloro-1,2-difluoroethane can be used to calculate the conformational population of the racemic system because the physical characteristics of chlorine and fluorine atoms are very similar and occupy the same positions in the molecule (Figure 13). For the trans conformers of meso and racemic 1,2-dichloro-1,2-difluoroethane, the hydrogen atoms are located trans to each other. In the trans meso conformer of 1,2-dichloro-1,2-difluoroethane, the chlorine atoms are positioned trans to each other as are the fluorines, but,

TABLE XXI

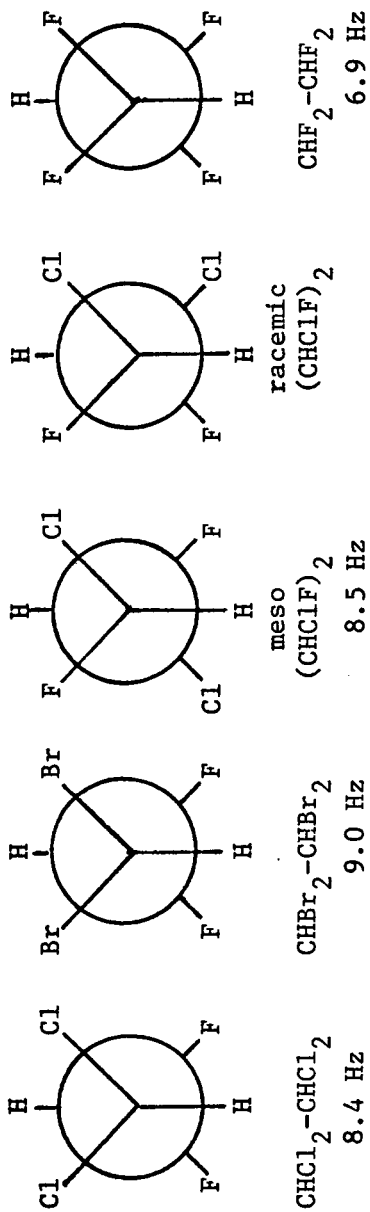
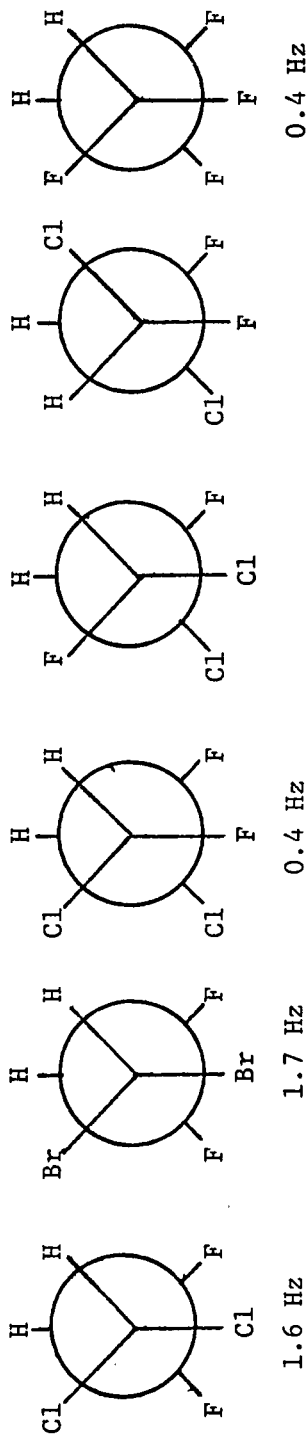
EXPERIMENTAL COUPLING CONSTANTS (HERTZ) FOR
RACEMIC 1,2-DICHLORO-1,2-DIFLUOROETHANE

<u>Additive</u>	$\underline{3J_{HH}}$	$\underline{3J_{FF}}$	$\underline{2J_{HF}}$	$\underline{3J_{HF}}$
90% perfluoroheptane	4.9	18.6	50.4	6.1
90% n-pentane	4.8	19.2	49.9	6.4
90% n-hexane	5.0	19.2	49.7	6.5
90% n-heptane	5.0	19.1	49.6	6.3
90% n-nonane	4.8	19.2	49.5	6.3
90% n-decane	4.9	19.1	49.6	6.4
90% cyclohexane	4.7	19.6	49.9	6.4
90% bromine	3.9	20.8	49.1	7.4
pure material	4.1	20.1	49.0	7.3
90% n-pentanol	3.7	20.5	48.6	7.4
90% 2-butanol	3.9	20.4	48.2	8.0
90% n-butanol	3.8	20.5	48.6	7.5
90% 2-propanol	3.9	20.5	48.4	8.0
90% cyclohexanone	4.7	19.6	49.9	6.4
90% n-propanol	3.5	20.2	48.7	7.5
90% ethanol	3.2	20.7	48.7	8.1
90% methanol	3.4	20.5	48.4	8.3
90% acetonitrile	2.7	20.8	48.0	9.0

in the trans conformer of the racemic molecule, the chlorines are positioned trans to fluorines. In general, the two conformers are different but the $^3J_{\text{HH}(\text{trans})}$ and $^3J_{\text{HH}(\text{gauche})}$ coupling constants are not affected by the change of atoms. Figure 16 shows $^3J_{\text{HH}(\text{trans})}$ and $^3J_{\text{HH}(\text{gauche})}$ coupling constants of different tetrahaloethanes, along with the Newman projections. These molecules have a similar geometric arrangement to meso and racemic 1,2-dichloro-1,2-difluoroethane and their coupling constants are similar.

The $^3J_{\text{FF}(\text{trans})}$ and $^3J_{\text{FF}(\text{gauche})}$ coupling constants of meso 1,2-dichloro-1,2-difluoroethane cannot be used to calculate the conformational population of the racemic system. In the trans conformer of racemic 1,2-dichloro-1,2-difluoroethane (Figure 13), the two fluorine atoms are positioned gauche to each other; the similar situation is found in the gauche conformer of the meso molecule. The difference between the gauche and trans conformers is that the trans conformer of the racemic molecule has a dipole moment of 0.45 Debye where the gauche conformer of the meso molecule has a dipole moment of 2.025 Debye; therefore, the $^3J_{\text{FF}}$ coupling constants are affected by the dipole change.

The $^3J_{\text{HF}(\text{trans})}$ and $^3J_{\text{HF}(\text{gauche})}$ coupling constants of meso 1,2-dichloro-1,2-difluoroethane cannot be used to calculate the conformational population of the racemic system. In the trans conformer of racemic 1,2-dichloro-1,2-difluoroethane (Figure 13), the chlorine atoms are located gauche to each other but in the trans conformer of the meso molecule the chlorine atoms are located trans to each other. The different positions occupied by the

$^3J_{\text{HH}}(\text{trans})$ Coupling Constants $^3J_{\text{HH}}(\text{gauche})$ Coupling ConstantsFigure 16. Comparison of $^3J_{\text{HH}}(\text{trans})$ and $^3J_{\text{HH}}(\text{gauche})$ Coupling Constants in Tetrahaloethanes*

* taken from reference 60

chlorine atoms affect the $^3J_{\text{HF}}$ coupling constants.

H. Effect of Solvent Concentration on Conformer
Population of Meso 1,2-dichloro-
1,2-difluoroethane

Table XXII lists the percentages of meso conformers of 1,2-dichloro-1,2-difluoroethane as a function of concentration and the ^1H NMR experimental coupling constants. Again, ^1H NMR is employed to obtain the percentages of meso conformers. The concentration study was carried out in two parts: (1) the effect was examined over a broad range, from zero to 90 percent additive with acetonitrile; and, (2) the effect was examined over a narrow range, from 90 to 99 percent additive with cyclohexane. For the broad range, the results indicate that as the concentration of the additive increases the conformational population changes. For the narrow range, the results indicate that there is no change in the conformational population.

I. Temperature Effect on Conformer Population
of Meso and Racemic 1,2-dichloro-
1,2-difluoroethane

Table XXIII lists the percentages of meso and racemic conformers of 1,2-dichloro-1,2-difluoroethane as a function of temperature and the ^1H NMR experimental coupling constants. Again, the ^1H NMR is employed to obtain the percentages of meso and racemic conformers. The temperature range for the study is from room temperature to -90°C in meso and to -100°C in racemic. The difference of temperatures for the two molecules is that meso 1,2-dichloro-

TABLE XXII

CONCENTRATION EFFECT ON CONFORMER POPULATION OF
MESO 1,2-DICHLORO-1,2-DIFLUOROETHANE

<u>Additive</u>	<u>Experimental Coupling Constants (Hertz)</u>				<u>Conformer Population</u>	
	$\frac{3}{J_{HH}}$	$\frac{3}{J_{FF}}$	$\frac{2}{J_{HF}}$	$\frac{3}{J_{HF}}$	<u>% Trans</u>	<u>% Gauche</u>
0% solvent	3.7	26.1	48.7	7.3	42.0	58.0
34% acetonitrile	3.2	24.9	48.7	8.1	36.0	64.0
59% acetonitrile	3.0	24.4	48.4	8.7	33.0	67.0
90% acetonitrile	2.8	24.0	48.6	8.8	31.7	68.3
90% cyclohexane	4.9	29.3	49.2	5.3	56.2	43.8
95% cyclohexane	4.9	29.5	49.2	5.3	56.2	43.8
99% cyclohexane	4.9	29.7	49.3	5.2	56.5	43.5

TABLE XXIII

 TEMPERATURE EFFECT ON CONFORMER POPULATION OF
 MESO AND RACEMIC 1,2-DICHLORO-
 1,2-DIFLUOROETHANE

90% Additive	Temperature	Experimental Coupling Constants (Hertz)			Conformer Population		
		$^3J_{HH}$	$^3J_{FF}$	$^2J_{HF}$	$^3J_{HF}$	% Trans	% Gauche
Meso							
n-pentane	25 °C	4.7	29.0	49.2	5.6	54.3	45.7
n-pentane	- 60 °C	5.2	30.5	48.7	4.8	60.5	39.5
n-pentane	- 80.0 °C	5.3	30.6	48.8	4.8	60.9	39.1
n-pentane	- 90.0 °C	5.3	30.8	48.9	4.5	62.1	37.9
Racemic							
n-pentane	25 °C	4.8	19.2	49.8	6.2	54.3	45.7
n-pentane	- 60.0 °C	5.1	20.1	49.8	6.1	58.6	41.4
n-pentane	- 80.0 °C	5.2	20.0	49.9	6.0	59.0	41.0
n-pentane	- 80.0 °C	5.2	20.2	49.8	6.1	59.0	41.0
n-pentane	-100.0 °C	5.5	20.1	50.0	6.0	63.0	37.0

1,2-difluoroethane precipitated out of solution at -90°C . Pentane is employed as the solvent for both systems and the percentage of additive is held constant at 90 percent. The results indicate that as temperature decreases the conformational population increases toward the nonpolar conformers for both meso and racemic 1,2-dichloro-1,2-difluoroethane.

J. Conformational Population of Cis and Trans
1,2-dichlorohexafluorocyclobutane

In a four member ring, there are three possible conformations: (1) substituents may be axial-equatorial; (2) substituents may be equatorial-equatorial; and, (3) substituents may be axial-axial. From Figure 14, cis-1,2-dichlorohexafluorocyclobutane has only one conformer, namely, the axial-equatorial but trans has two conformers, the axial-axial and equatorial-equatorial.

1,2-dichlorohexafluorocyclobutane was originally selected for this research to avoid any conformational effects. Cis-1,2-dichlorohexafluorocyclobutane does not have any conformers but trans- does have conformers. To prove that a conformational effect does not exist in trans, ^{19}F NMR spectra were taken in solvents of different dielectric constants. Table XXIV shows the results of ^{19}F NMR experiments. The ^{19}F NMR spectra of the two isomers are distinct, each consists of a single line plus a symmetrical AB quartet. The single line is due to the CFC1 fluorine nuclei and the quartet is due to CF_2 resonances. The quartets are analyzed as AB spectra.⁶⁴ The chemical shift between the two fluorine nuclei in

TABLE XXIV

¹⁹F NMR OF CIS AND TRANS 1,2-DICHLORO-
HEXAFLUOROCYCLOBUTANE

	Experimental Coupling		Chemical Shift		Change in Chemical Shift		Chemical Shift (δ) of the Single Line (ppm)
	Constant (J_{AB}) of AB Quartet (ppm)	(δ_{AB}) of AB Quartet (ppm)	(δ_{AB}) of AB Quartet (ppm)	Shift ($\Delta\delta_{AB}$) of AB Quartet (ppm)	Shift ($\Delta\delta_{AB}$) of AB Quartet (ppm)		
pure trans	206.8	38.71, 34.79	38.71, 34.79	3.92	3.92	33.65	
90% heptane - trans	206.8	38.21, 34.34	38.21, 34.34	3.86	3.86	32.95	
90% pentanol - trans	206.8	38.31, 34.44	38.31, 34.44	3.87	3.87	32.95	
pure cis	206.8	42.40, 30.75	42.40, 30.75	11.65	11.65	24.25	
90% heptane - cis	206.8	41.70, 30.15	41.70, 30.15	11.55	11.55	23.70	
90% pentanol - cis	206.8	42.00, 30.43	42.00, 30.43	11.57	11.57	23.80	

* Hexafluorobenzene was employed as an internal standard.

the CF_2 groups is 11.7 (hexafluorobenzene = 0) for cis and 3.9 ppm for trans. The cis has the greater chemical shift because of the symmetry of the isomer. If a conformational effect did exist in trans 1,2-dichlorohexafluorocyclobutane then there would have been a change in the experimental coupling constants and the chemical shift between the two fluorine nuclei in the AB quartet with different solvents.

K. Summary of Conformational Analysis

The conformational population of meso and racemic 1,2-dichloro-1,2-difluoroethane were determined by ^1H NMR. The ^1H NMR shows that the conformational population of both isomers can be varied by changing the nature of the solvent. The changes in conformational population are controlled by the dielectric constant of the solvent. Solvents of high dielectric constant will force the molecule to favor polar conformations and solvents of low dielectric will favor the nonpolar conformations.

The combination of calculated individual conformer dipole moments and experimental dipole moments shows that the two gauche conformers of racemic 1,2-dichloro-1,2-difluoroethane are very similar to the gauche conformer of the meso. In general, meso and racemic 1,2-dichloro-1,2-difluoroethane have about the same conformational population and solvents affect both molecules equally.

Cis and trans 1,2-dichlorohexafluorocyclobutane are treated as separate compounds. Cis-1,2-dichlorohexafluorocyclobutane has only one conformer while the trans species have two conformers.

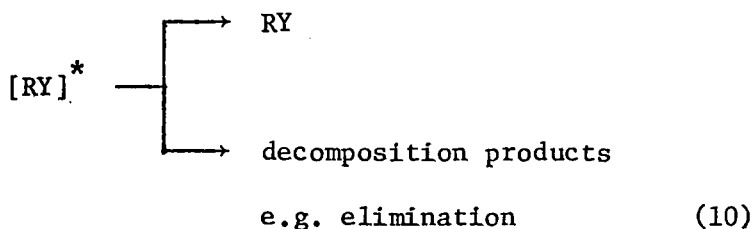
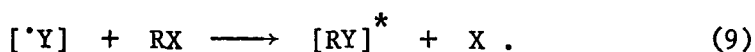
However, the above NMR results have given no indication that the conformer population depends on the nature or concentration of the solvent.

X. DISCUSSION

A. Introduction

As previously mentioned, there are two basic mechanisms which have been presented to explain the stereochemical course for the liquid phase hot atom substitution reaction.

(1) One-step molecular reaction or hot direct replacement



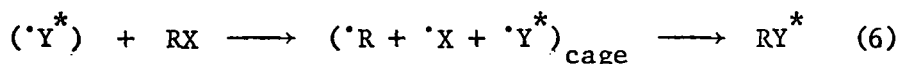
The primary hot substitution product $[RY]^*$ with high excitation energy can either decompose or stabilize through collisional de-excitation.

The important feature of this mechanism is that the reaction is stereospecific. The initial configuration of RX has a major influence on the configuration of the product RY. In hot tritium substitution reactions, only the retained product would be expected and the inverted product would be forbidden.

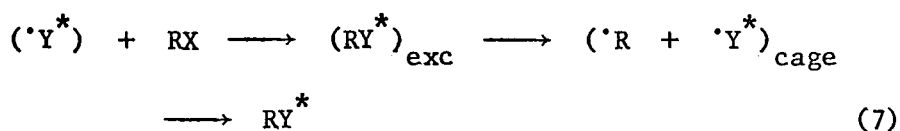
Solvents may affect the one-step molecular reaction in two ways: (1) the nature of the solvent may induce conformational changes in RX before the hot reaction takes place, and (2) the physical properties of the solvent, such as density, viscosity, and molecular

size could stabilize to a different degree the primary excited product $[RY]^*$.

(2) Caged radical-radical combination. The radical-radical cage reaction occurs either following a hot displacement of a halogen by a recoil atom with excess kinetic energy



or a hot one-step substitution after excitation decomposition of the primary excited product.



The results of the reaction proceeding by this mechanism would differ from the one-step molecular substitution by allowing for a lower degree of stereospecificity. The configuration of product RY could depend to a lesser degree on the configuration of RX because cage effects allow the radical ($R\cdot$) to undergo possible conformational or configurational changes before combination with $(\cdot Y^*)$ occur, leading to a change in the stereochemical course of the hot reaction. The nature of the solvent can lead to certain conformational preferences of the radical ($R\cdot$) or allow the radical ($R\cdot$) to obtain more or less rapid planarity. Solvents with strong solute-solvent interactions may force the radical to maintain its initial conformation (retained product) where weak solute-solvent interactions may allow the radical to become planar (racemization of products before recombination takes place). The role of the solvent in the stereochemical course of the liquid phase hot atom

substitution reaction could be a key factor to distinguish the one-step molecular reaction from caged radical-radical reactions.

Richardson and Wolfgang,⁴³ in a study of the density effect on the yield of hot ^{18}F reactions with CH_3F , have postulated a cage effect. Identical behavior has been shown in subsequent investigations, $^{38}\text{Cl}/(\text{CHClF})_2$, $^{80}\text{Br}/\text{CH}_3\text{F}$, $^{123}\text{I}/\text{C}_2\text{H}_6$, $^{128}\text{I}/\text{C}_2\text{H}_2$ and $^{18}\text{F}/\text{CH}_3\text{CF}_3$ systems.^{1,65-68} Figure 17 shows the density effect on substitution product yield. In the region of lowest gas densities (region I), the initial increase in yield is due to enhanced de-excitation stabilization of highly excited primary products which are formed by direct substitution reactions. The substitution product levels off when excited species have been stabilized (region II). At high gas densities (region III), a second increase, according to Richardson and Wolfgang, is due to caged radical-radical combination reactions. Manning and Root⁶⁹ have studied the ^{18}F for F substitution in CH_3CF_3 and CH_3CHF_2 by using a combined density-variation and mechanism-elucidation technique. Although these authors question the Richardson Wolfgang explanation, they also came to the conclusion that primary hot substitution reactions exhibit caging at high densities.

B. ^3H for H Substitution in 1,2-dichloro-1,2-difluoroethane

Substitution with inversion of configuration is almost negligible in the gas phase for hot tritium. Stöcklin et. al.^{1,3} have shown the ^3H for H substitution in 1,2-dichloro-1,2-difluoroethane

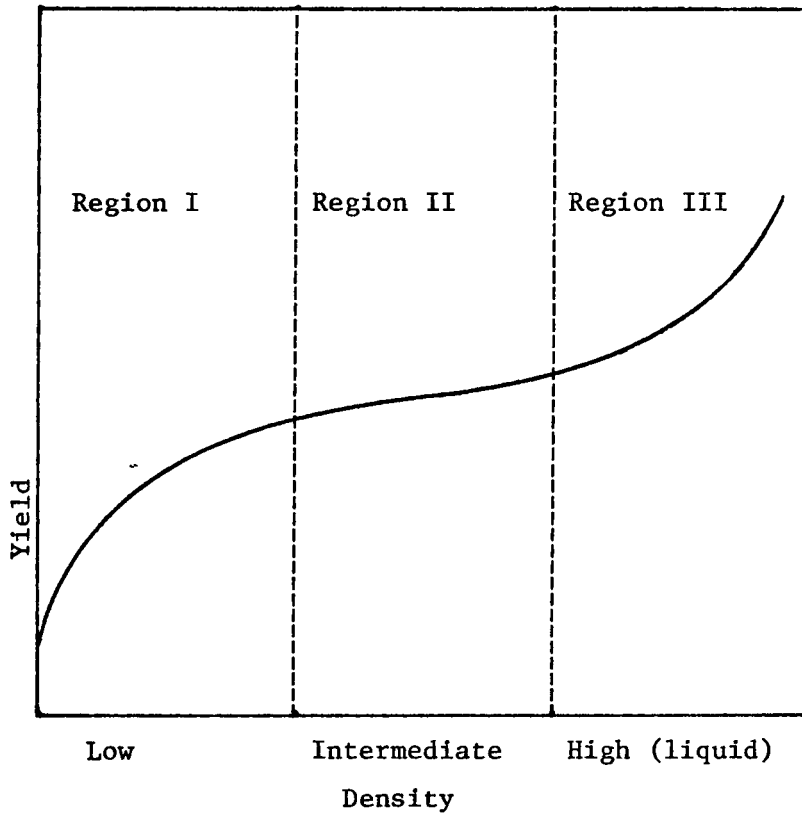


Figure 17. Density Effect on Substitution Product Yield

is greater than 95 percent retention in the gas phase. These investigators have also demonstrated for the same system that 90 percent of all recoil atoms end up in an inorganic form. The mechanism which best explains tritium reactions and gas phase hot atom substitution reactions is the one-step molecular mechanism (Richardson and Wolfgang impact model). Retention of configuration is due to head-on collisions between the hot atom and the organic halide. The high yield for the formation of inorganic compounds is explained by the greater probability of glancing collisions between the hot atom and the organic halide (abstraction reactions). Abstraction reactions have a lower energy requirement than substitution reactions.⁷

The results of the present study have shown that in the liquid phase, ³H for H substitution in 1,2-dichloro-1,2-difluoroethane proceeds predominately with retention of configuration (Table X). The results of the gas phase hot reaction differs slightly from the liquid phase reaction of the pure material (96 percent retention to 92 percent retention). As reported in this work, solvents do not influence the stereochemical course of the hot reaction (100 percent retention for cyclohexane and 92 percent for n-propanol). The experimental error for liquid phase hot atom substitution reaction is approximately five percent. The results indicate that hot recoil tritium undergoes similar reactions in the gas and liquid phases.

Most mechanisms for liquid phase hot atom substitution reactions consider caging as its central concept. Hot recoil tritium substitution reactions do not show a solvent effect; therefore,

caging is not an important factor in this system. Tritium could be considered an exception because it may be too small to be trapped in a solvent cage from which it will diffuse out and its collisional time may be too rapid to allow an intermediate radical to undergo conformational changes.

The mechanism which best explains the liquid phase ^3H for H hot atom substitution reactions is the Richardson Wolfgang impact model.⁷ Inversion is a forbidden mode because of the time scale for Walden inversion to take place. The time period begins with a hot tritium striking a substrate molecule from the backside and recoiling away before the molecule can invert its orbitals to hold the hot atom. If inversion is a higher energy process than retention, attack from the backside, probably deposits so much kinetic energy that the molecule will fall apart. The radiochemical yields are characteristically low because the energy requirement necessary for retention has a narrow range. The impact model predicts no solvent effect.

C. ^{38}Cl for Cl Substitution in 1,2-dichloro-
1,2-difluoroethane and 1,2-dichloro-
hexafluorocyclobutane

Evidence for caging in liquid phase hot atom substitution reactions centers around two basic types of experiments: (1) the density-variation study on substitution product yield for the transition from gas to liquid phase and (2) the solvent influences on the stereochemical course for substitution reactions at asymmetric carbon atoms. The only mechanism considered for condensed phase

hot atom reactions has been for a long time the caged radical-radical combination. The hot direct replacement mechanism has in the past been ruled out because of its failure to explain the decrease in stereospecificity at high gas densities and solvent effects.

Stöcklin and coworkers have studied the liquid phase ³⁸Cl for Cl substitution in diastereomeric 2,3-dichlorobutane⁴ and density-variation study on diastereomeric 1,2-dichloro-1,2-difluoroethane.¹ On the basis of an observed solvent effect and a decrease in stereospecificity at high gas densities, Stöcklin has suggested that substitution occurs via direct replacement with collisional stabilization of a "caged complex". The basic argument used to exclude the caged radical-radical mechanism is that hot atoms which remain as a result of the break-up of primary reactions should be immediately scavenged via hydrogen abstraction from one of the hydrogen-containing solvent molecules. The hydrogen abstraction reaction removes the hot atom so that it will not be subject to caged radical-radical combination reactions. Additional evidence to support the "cage complex" model has been presented by Rack and coworkers.⁶⁷ These investigators have studied the reaction of hot iodine with acetylene and have found an increase of combined C₂H₅I and C₂H₃I product yield with decreasing normalized intermolecular distance (λ/σ) where λ is the intermolecular distance between centers of spheroidal molecules of diameter σ . These same investigators also observed a decrease in the substitution product yield in the density-variation study of the acetylene system.

The experimental results obtained in the present investiga-

tion must be discussed in terms of two models: (1) evidence which supports a hot one-step reaction mechanism or "caged complex" and (2) evidence which supports a caged radical-radical combination mechanism.

Stöcklin et. al.^{67,70} have proposed from work on systems such as 2,3-dichlorobutane that the nature of the solvent causes a conformational effect which controls the stereochemical course of the hot reaction and which would support the one-step mechanism. Thus as a first step we decided to see whether such a conformational effect can be observed in the present work. Figures 18 and 19 show the relationship between the dielectric constant of the solvents and the conformational population of meso and racemic 1,2-dichloro-1,2-difluoroethane. The percentage of gauche conformer is obtained from ^1H NMR. Cyclohexanone is the only solvent which seems to deviate from the curve in both Figures 18 and 19. Figure 19 has a greater scattering of points because only $^3\text{J}_{\text{HH}}$ was used to determine the conformational population where values obtained for Figure 18 was taken from three different coupling constants.

In order to determine whether a conformational effect exists in the ^{38}Cl for Cl substitution in meso and racemic 1,2-dichloro-1,2-difluoroethane, the conformational population was plotted versus the retention to inversion ratio. Figures 20 and 21 show indeed a relationship between conformational population and the retention to inversion ratio but bromine and acetonitrile do deviate drastically from the curve in both plots. Figure 18 and 19, where the dielectric constant is plotted versus the conformational population,

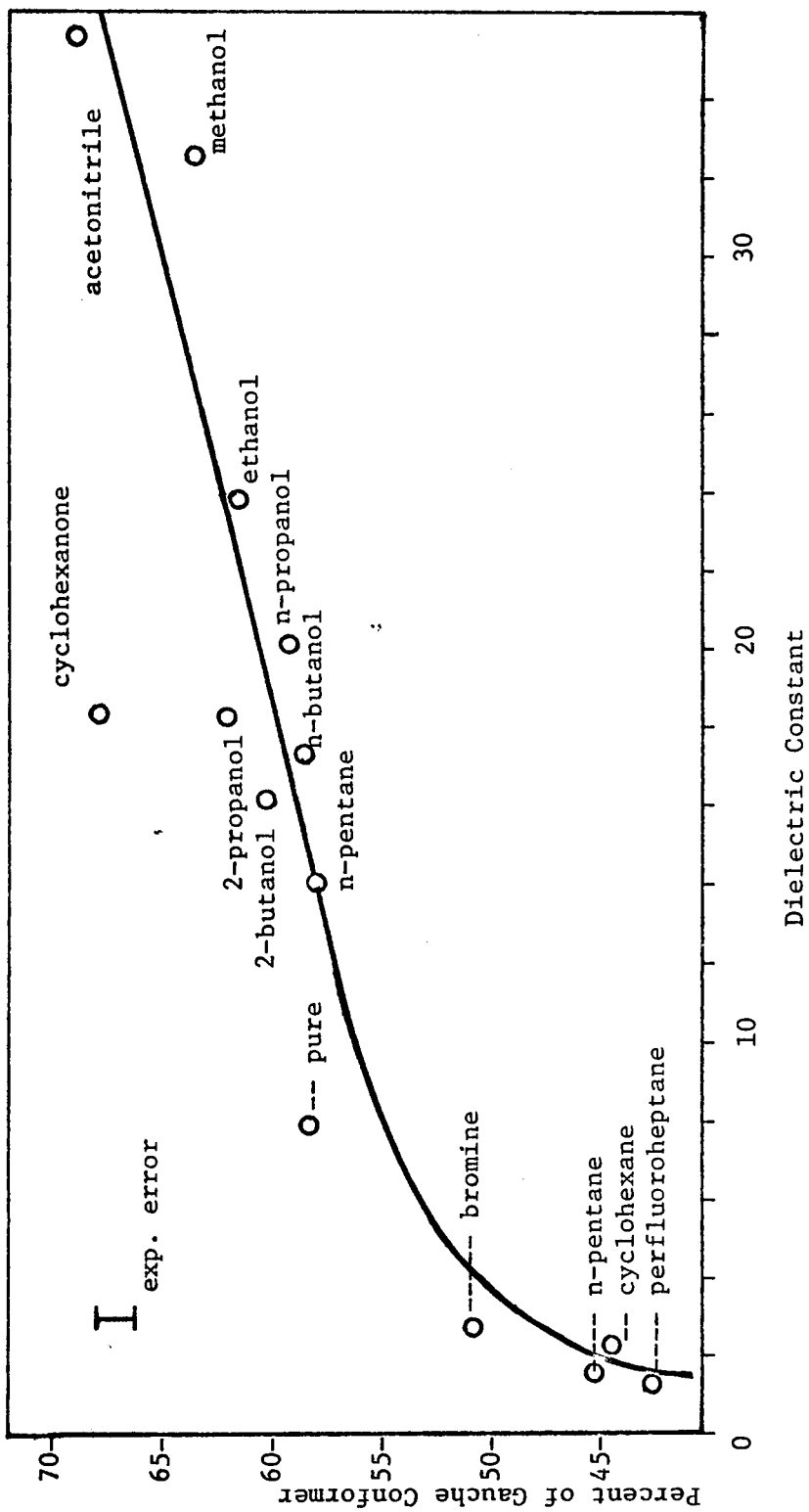


Figure 18. Conformational Population of Meso 1,2-Dichloro-1,2-Difluoroethane as a Function of Dielectric Constant

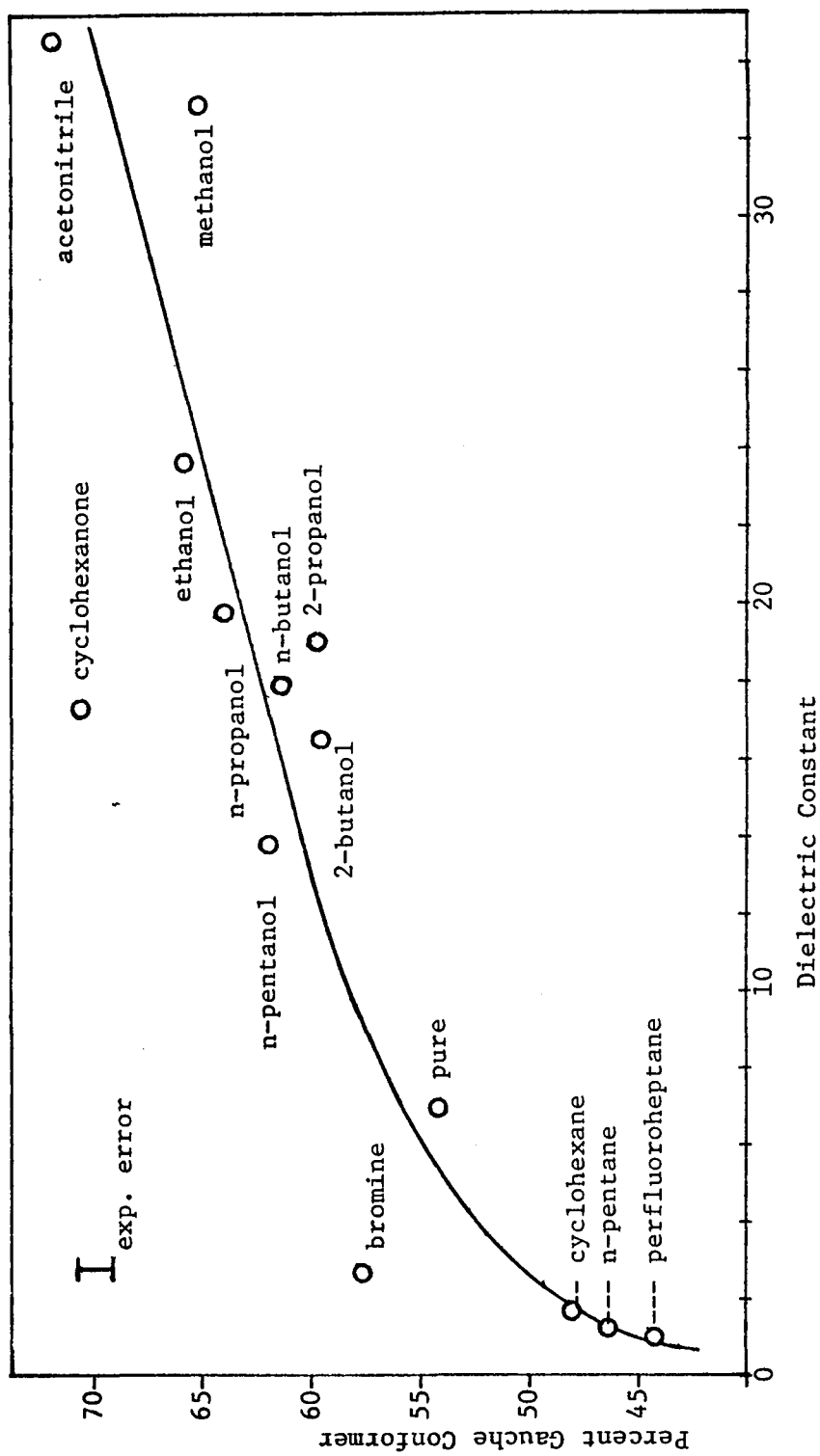


Figure 19. Conformational Population of Racemic 1,2-Dichloro-1,2-Difluoroethane as a Function of Dielectric Constant

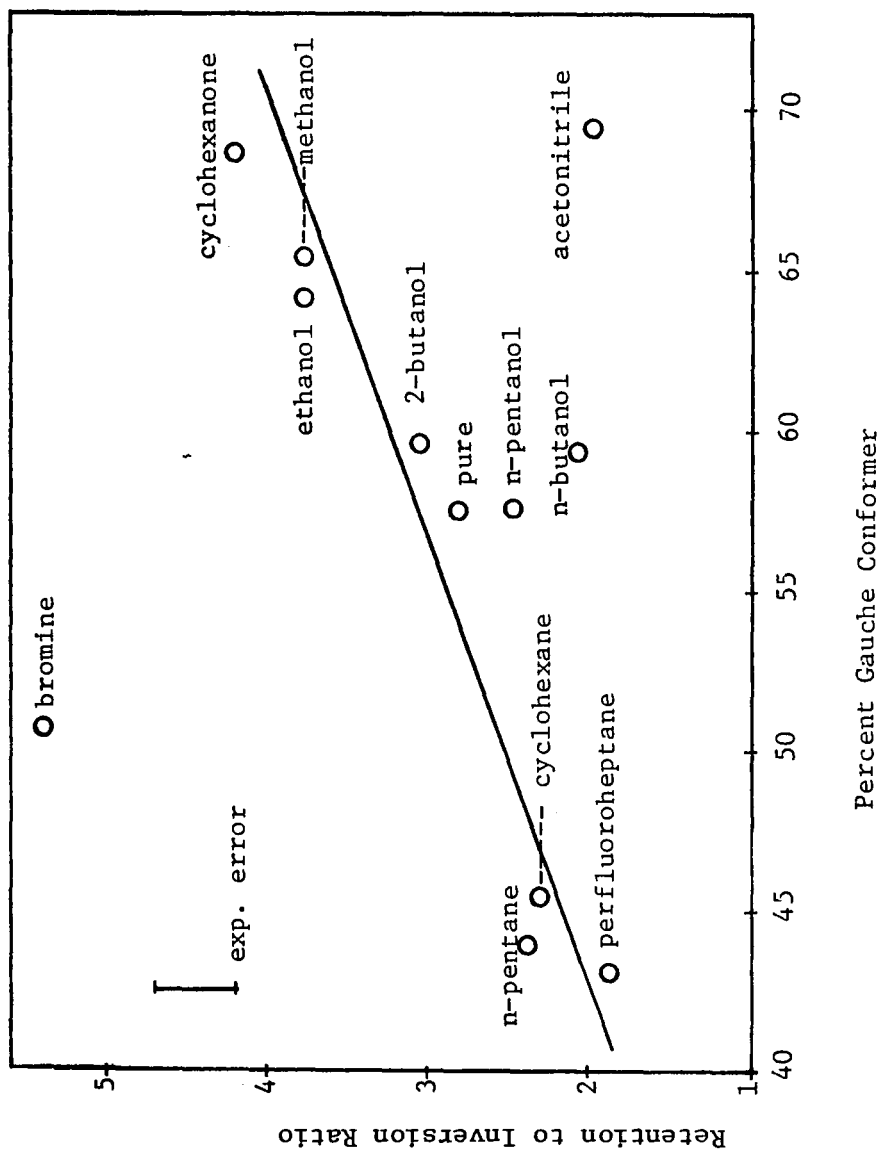


Figure 20. Conformational Population of Meso 1,2-Dichloro-1,2-Difluoroethane as a Function of the Retention to Inversion Ratio of Meso 1,2-Dichloro-1,2-Difluoroethane

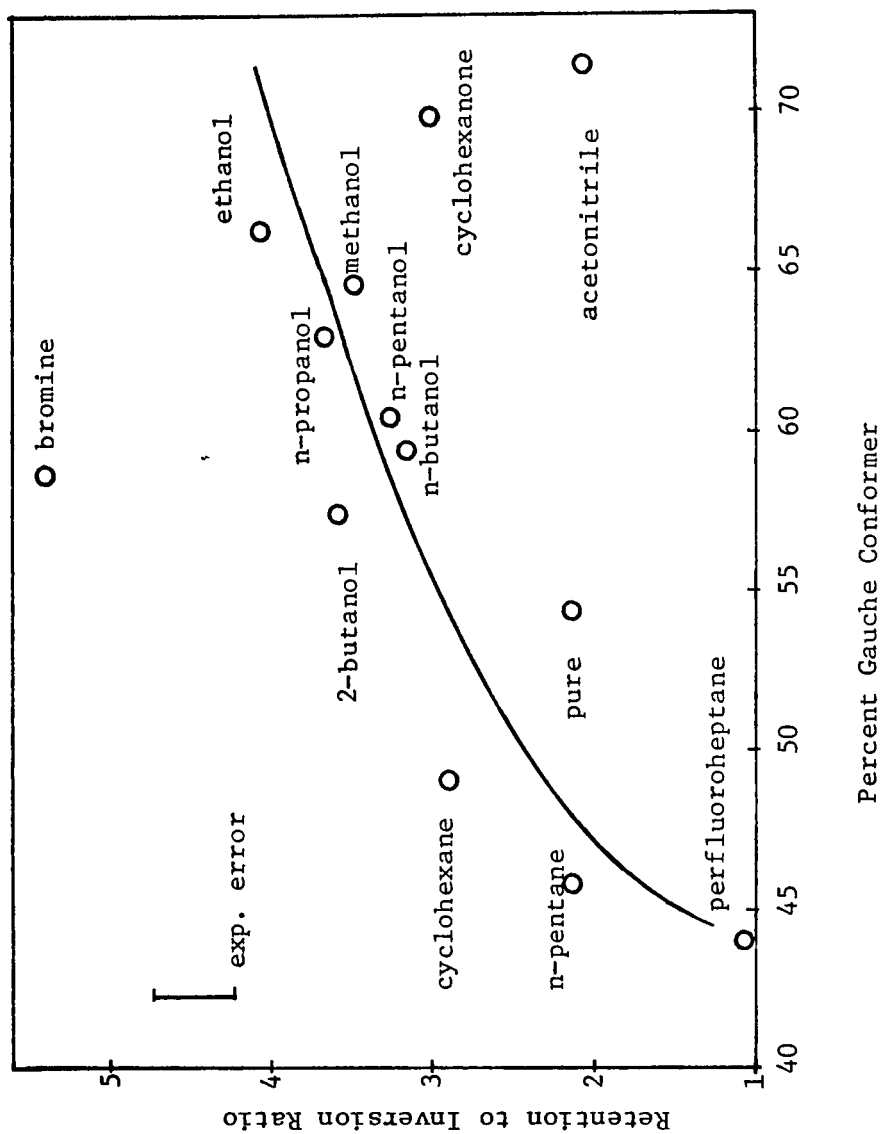


Figure 21. Conformational Population of Racemic 1,2-Dichloro-1,2-Difluoroethane as a Function of the Retention to Inversion Ratio of Racemic 1,2-Dichloro-1,2-Difluoroethane

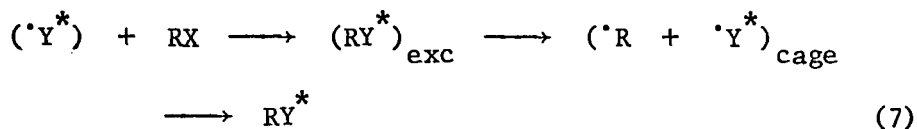
shows that bromine and acetonitrile influence the conformational population of both meso and racemic 1,2-dichloro-1,2-difluoroethane in the same manner as the other solvents. If bromine and acetonitrile are indeed exceptions and the retention to inversion ratio is controlled by the conformational population, one should expect to see no dependence of this ratio in the 1,2-dichlorohexafluorocyclobutane system.

As proven earlier in this research, cis and trans 1,2-dichlorohexafluorocyclobutane have conformational populations which are independent of solvent. Furthermore, the cis molecule has only one conformer. Tables XI and XII list the retention to inversion ratios of cis and trans 1,2-dichlorohexafluorocyclobutane for various solvents. The results indicate that cyclohexane, heptane, and n-pentanol all give very high retentions of configurations and with an experimental error of five percent to ten percent one may assume that all three solvents have the same interaction in this system. Perfluoroheptane and the pure material, however, deviate drastically from the hydrogen containing solvents, as shown in Tables XI and XII. Perfluoroheptane, with a dielectric constant of 1.77, gives a retention to inversion ratio of 2.6 in the trans and 1.2 in the cis where heptane with a dielectric constant of 1.92 gives a retention to inversion ratio of 5.3 in trans and 7.1 in cis. The results of the 1,2-dichlorohexafluorocyclobutane system indicate that a conformational effect does not exist and that the observed solvent effect must have a different origin. Additional support for this contention comes from the study of the liquid

phase reaction ^{38}Cl for Cl substitution in 2,4-dichloropentane by Ache and Wu,⁷¹ where it has been shown that the stereochemical course of the ^{38}Cl for Cl substitution in 2,4-dichloropentane, which has only one major conformer in the meso molecule and one major conformer in the racemic molecule, exhibits a solvent effect.

Ache and Wu⁷¹ have explained these results in terms of solute-solvent interactions. In terms of a one-step substitution mechanism, one could assume that the reactants interact strongly with the surrounding solvent molecule, the excess energy of the retained product formed is quickly dissipated and the product stabilized. In solvents of low dielectric constant where there is less interaction, the energy dissipation proceeds less rapidly and less of the retained product formed in a high energy substitution becomes stabilized.

In terms of the caged radical-radical combination mechanism,



recombination may occur following ^{38}Cl for Cl substitution and subsequent break-up of the excited intermediate state. Recombination can occur either by retention or by inversion of configuration. The ratio of retained or inverted product formed depends to a certain degree on the time factor for recombination of the radicals and the time required for the organic radical to achieve a planar configuration. In the case of strong interaction between the intermediate radical and the surrounding molecules the radical will

most likely not achieve planarity before recombination takes place and recombination will occur resulting in a labelled molecule which maintains the same configuration as it achieved in the primary step. In the case of weakly interacting solvents, racemization of the intermediate organic radical becomes highly probable. Figures 22 and 23 show the retention to inversion ratios of ^{38}Cl for Cl substitution in 1,2-dichloro-1,2-difluoroethane as a function of the interaction term $(\epsilon - 1)/(2\epsilon + 1)$.

The parameter $(\epsilon - 1)/(2\epsilon + 1)$ ⁷² can be related to the degree of intermolecular interaction between the reactants and the surrounding solvent molecules. The magnitude of the intermolecular interaction may be obtained from the free energy change which occurs when a solute molecule is transferred from a vacuum to a solvent.^{73,74} The free energy change is governed by two terms: (1) the cavity term and, (2) the interaction term. The cavity term represents the energy required to create a hole in the liquid which is a function of surface tension. The interaction term is a result of the action of the solvent on the solute when the solute molecule is introduced into a hole. The interaction term is related to the dipole and multipole moments of the solute molecule, the molecular volume (a^3) of the solute and the dielectric constant (ϵ) of the solvent.

The results of the 1,2-dichlorohexafluorocyclobutane system show consistently a high retention of configuration for hydrogen-containing solvent which again may be due to immediate stabilization of the excited intermediate state $[\text{RY}]^*$. These solvents can

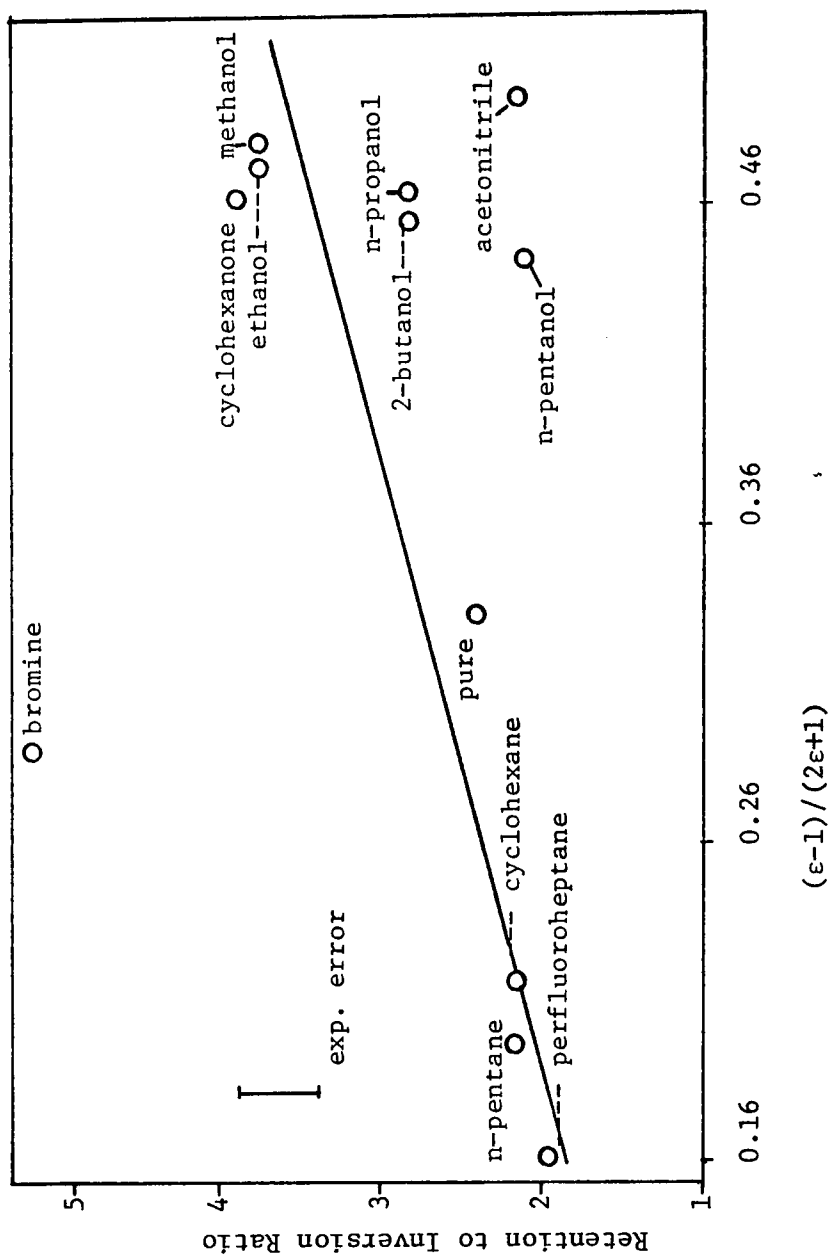


Figure 22. Interaction Term $(\epsilon-1)/(2\epsilon+1)$ of Solvents as a Function of the Retention to Inversion Ratio of Meso 1,2-Dichloro-1,2-Difluoroethane

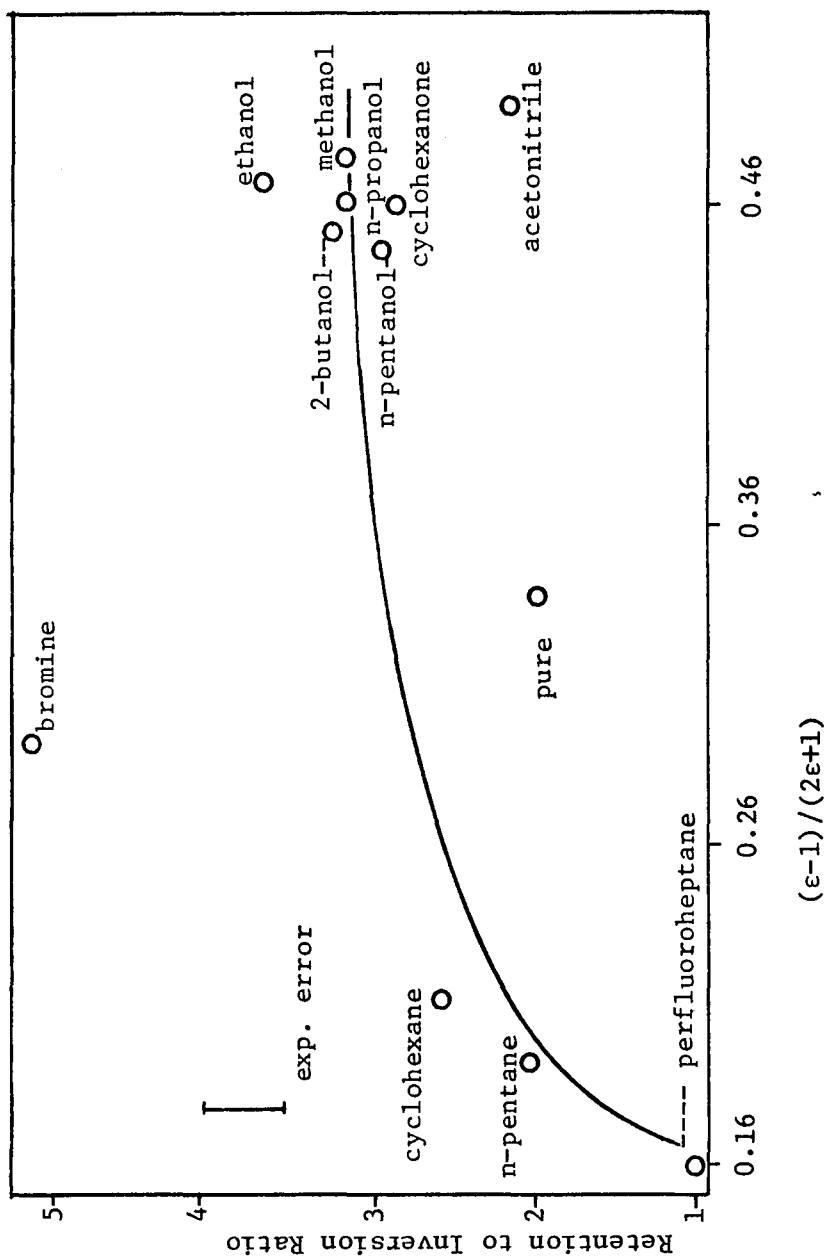


Figure 23. Interaction Term $(\epsilon-1)/(2\epsilon+1)$ of Solvents as a Function of the Retention to Inversion Ratio of Racemic *i*,2-Dichloro-1,2-Difluoroethane

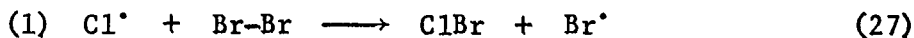
probably quickly dissipate the excess energy of the excited intermediate state and stabilize the product. In terms of the radical-radical recombination mechanism, one could argue that the time scale for recombination of radicals in the solvent cage may be too rapid for conformational changes by the radical (R^{\cdot}). Perfluoroheptane and the pure material have a much lower retention of configuration than the hydrogen-containing solvents either due to lack of immediate stabilization of the excited intermediate $[RY]^*$ or the perfluoroheptane and the pure material may have a very weak solute-solvent interaction prolonging the time available for recombination of radicals in the solvent cage for conformational changes by the radical (R^{\cdot}). The results of the experiments did not allow a distinction between the two experiments but are consistent with the concept of solute-solvent interactions. In order to find some evidence which would either favorably support the one- or two-step mechanism, it may be important to discuss the anomalies found in the presence of solvents such as bromine, acetonitrile and perfluoroheptane.

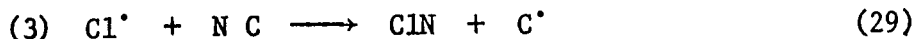
In the ^{38}Cl for Cl substitution in meso and racemic 1,2-dichloro-1,2-difluoroethane, bromine and acetonitrile deviated drastically from hydrogen-containing solvents; so did perfluoroheptane but not to the extent of the other two. In the ^{38}Cl for Cl substitution in cis and trans 1,2-dichlorohexafluorocyclobutane, perfluoroheptane differed significantly from hydrogen-containing solvents, when an attempt was made to plot the retention to inversion ratio as a function of the interaction term. Acetonitrile, with a

dielectric constant of 35.9, gives a retention to inversion ratio of 2.2 for meso and 2.0 for racemic 1,2-dichloro-1,2-difluoroethane, whereas bromine, with a dielectric constant of 3.09, gives a ratio of 5.2 for meso and 5.3 for racemic, and perfluoroheptane, with a dielectric constant of 1.77, gives a ratio of 1.9 for meso and 1.0 for racemic. It should be pointed out that perfluoroheptane which is a low dielectric material gives a lower ratio than pentane even though their dielectric constants are similar (1.77 to 1.84).

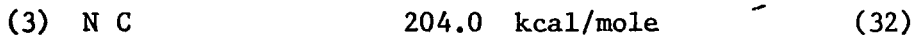
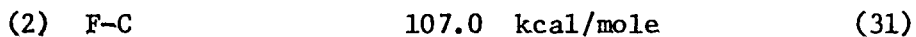
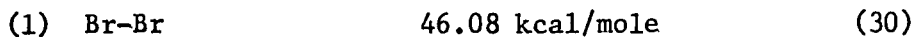
Why do perfluoroheptane, bromine, and acetonitrile react in an unexpected manner? The answer may be in the nature of the cage wall formed by various solvents. Bromine and perfluoroheptane do not contain any hydrogen atoms. Acetonitrile does contain hydrogen atoms but might form the solvent cage wall with the nitrogen end of the molecule pointing inward to the trapped substrate molecule and hot atom. The reasons for this behavior are: (1) the nitrogen end of the molecule would be either neutral or slightly positive; and, (2) there would be less crowding with nitrogen facing inward. The result of this behavior is molecules form the solvent cage.

In terms of a caged radical-radical combination mechanism, one could argue that "self scavenging" occurs where the ^{38}Cl formed by the break up of the primary product can abstract an atom from the solvent cage wall. The possible abstraction reactions which may occur between the ^{38}Cl and bromine, perfluoroheptane and acetonitrile are:

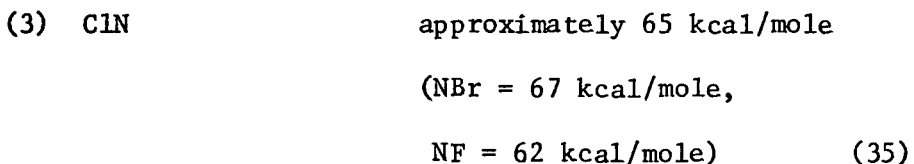
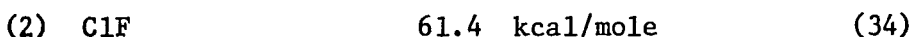
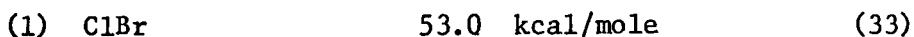




The bond dissociation energies are:⁷⁵



The bond strength energies are:⁷⁵



By subtraction of the bond dissociation energy from the bond strength energy, the heat of the reaction is estimated. The abstraction reaction of Br by Cl^\bullet from liquid bromine is exothermic (7 kcal/mole), F by Cl^\bullet from perfluoroheptane is endothermic (45.6 kcal/mole), and N by Cl^\bullet from acetonitrile is endothermic (139 kcal/mole). The bromine abstraction reaction could effectively lead to scavenging of the ^{38}Cl . Gas phase hot atom reactions generally show a high retention of configuration of the product. Thus one would expect that in those cases, where Cl is effectively scavenged, substitution occurs via retention of configuration. Additional supporting evidence for this assumption is the liquid phase hot tritium reactions where substitution occurs predominantly with retention of configuration. The actual experiments with bromine as solvent indeed show the expected high retention which is considerably higher than in any hydrogen-containing

solvent.

Solvents which have hydrogen atoms forming the interior walls of the solvent cage could also undergo abstraction reactions. The bond dissociation energy for most C-H and O-H bonds are of the order of 100 kcal/mole. The bond strength energy of HCl is 103 kcal/mole. The production of HCl by an abstraction reaction is exothermic by 3 kcal/mole; this value, however, is considerably less than for liquid bromine. The abstraction process may not be as efficient for hydrogen as for liquid bromine, and this would explain the lesser degree of retention observed in these reactions.

In the case of acetonitrile where abstraction reactions are not favored and where no scavenging of ^{38}Cl takes place, inversion of configuration of the product should become more probable. Inversion of configuration increases because the hot atom has more time to combine with the organic radical and thus the organic radical has more time to undergo conformational changes. The same argument can be applied for perfluoroheptane because its abstraction reaction is also endothermic. The experimental results indicate that perfluoroheptane gives a lower retention to inversion ratio than hydrogen-containing solvents with comparable dielectric constants. This would be expected from the thermodynamics for the production of HCl and ClF. It is difficult to explain these findings in terms of the one-step model; the two-step mechanism is favored as the most likely mechanism for the ^{38}Cl for Cl substitution process in these systems.

D. Summary

In summary, the degree of interaction between the intermediate radical and solvent governs the stereochemical course of the reaction. The solute-solvent interaction controls the time scale for relaxation processes, where the radical obtains planarity. This occurs if the probability for "self scavenging" is approximately equal for all the solvents used, usually for most hydrogen-containing compounds. If the cage wall is made up of reactive compounds such as liquid bromine, the chlorine formed in the decomposition is scavenged. The only products formed will be those which have a short time scale for combination compared to the scavenging process, namely, the retained product. For highly unreactive cage walls, such as acetonitrile and perfluoroheptane, the time scale for combination is prolonged in comparison to hydrogen-containing solvents; therefore, the stereospecificity of the reaction decreases.

XI. LITERATURE CITED

1. H. J. Machulla and G. Stöcklin, *J. Phys. Chem.* 78, 658 (1974).
2. Y. N. Tang, C. T. Ting and F. S. Rowland, *J. Phys. Chem.* 74, 675 (1970).
3. G. F. Palino and F. S. Rowland, *J. Phys. Chem.* 75, 1299 (1971).
4. L. Vasaros, H. J. Machulla and G. Stöcklin, *J. Phys. Chem.* 76, 501 (1972).
5. C. M. Wai, C. T. Ting and F. S. Rowland, *J. Amer. Chem. Soc.* 86, 2525 (1964).
6. R. R. Pettijohn, E. P. Rack and A. P. Wolf, "7th International Hot Atoms Symposium", Julich, 1973, p. 34.
7. R. Wolfgang, *Progr. Reaction Kinetics* 3, 97 (1965).
8. L. Szilard and T. A. Chalmers, *Nature* 134, 462 (1934).
9. E. Amaldi, E. Fermi, B. Pontecorvo, F. Rosetti and E. Segre, *Proc. Roy. Soc (London)* A149, 522 (1935).
10. E. Glüeckauf and J. Fay, *J. Chem. Soc.* 58, 390 (1936).
11. J. E. Willard, *Ann. Rev. Phys. Chem.* 6, 141 (1955).
12. J. E. Willard, *Nucleonics* 19, 61 (1961).
13. G. Harbottle and N. Sutin, *J. Phys. Chem.* 62, 1344 (1958).
14. A. P. Wolf, *Advan. Phys. Org. Chem.* 2, 201 (1964).
15. J. G. Campbell, *Adv. Inorg. Chem. Radiochem.* 5, 135 (1963).
16. R. Wolfgang, *Ann. Rev. Phys. Chem.* 16, 15 (1965).
17. G. Stöcklin, "Chemie Heisser Atome", Verlag Chemie, Weinheim, 1969.
18. D. S. Urch, *Inorg. Chem., Ser. 1*, 8, 149 (1972).
19. D. S. Urch, *Inorg. Chem., Ser. 2*, 8, 49 (1975).

20. C. M. Wai and F. S. Rowland, *J. Phys. Chem.* 71, 2752 (1967).
21. G. Friedlander, J. W. Kennedy and J. M. Miller, "Nuclear and Radiochemistry", John Wiley and Sons, New York, 1966, pp. 209, 337.
22. W. Schulze, "Advances in Activation Analysis", J. M. A. Leniham and S. J. Thomson, eds., 1, Academic Press, New York, 1969, p. 3.
23. L. K. Allison and M. Garcia-Munoz, "Atomic and Molecular Processes", D. R. Bates, ed., Academic Press, New York, 1962, p. 722.
24. H. A. Bethe and J. Ashklin, "Passage of Radiation through Matter", "Experimental Nuclear Physics", E. Segre, ed., 1, John Wiley and Sons, New York, 1953.
25. N. Bohr, *Phil. Mag.* 25, 10 (1913).
26. A. Dalgarno, "Atomic and Molecular Processes", D. R. Bates, ed., Academic Press, New York, 1962, p. 696.
27. H. S. W. Massey and E. Burhop, "Electronic and Ionic Impact Phenomena", Oxford University Press, Oxford, 1952, p. 441.
28. M. A. El Sayed, P. J. Estrup and R. Wolfgang, *J. Phys. Chem.* 62, 1356 (1958).
29. M. Marshall, C. Mackay and R. Wolfgang, *J. Amer. Chem. Soc.* 86, 4741 (1964).
30. L. Spicer and R. Wolfgang, *J. Chem. Phys.* 50, 3466 (1969).
31. R. J. Cross and R. Wolfgang, *Radiochim. Acta* 3, 112 (1964).
32. J. L. Thompson and W. W. Miller, *J. Chem. Phys.* 38, 247 (1963).
33. S. Yosmin and T. H. Davies, *J. Phys. Chem.* 56, 599 (1952).
34. C. M. Wai and F. S. Rowland, *J. Amer. Chem. Soc.* 90, 3638 (1968).
35. J. B. Evans, J. E. Quinlan, M. C. Sauer and J. E. Willard, *J. Phys. Chem.* 62, 1351 (1958).
36. J. E. Willard, "Chemical Effects of Nuclear Transformations I", I.A.E.A., Vienna, 1965, p. 215.
37. S. Goldhaber and J. E. Willard, *J. Amer. Chem. Soc.* 74, 318 (1952).

38. A. Rosenberg and R. Wolfgang, *J. Chem. Phys.* 41, 2159 (1964).
39. J. Franck and E. Rabinowitch, *Trans. Faraday Soc.* 30, 120 (1934).
40. W. F. Libby, *J. Amer. Chem. Soc.* 62, 1393 (1940).
41. C. Lu and S. Sugden, *J. Chem. Soc.*, 1273 (1939).
42. W. E. Rice and J. E. Willard, *J. Amer. Chem. Soc.* 75, 6159 (1953).
43. A. E. Richardson and R. Wolfgang, *J. Amer. Chem. Soc.* 92, 3480 (1970).
44. J. M. Miller, J. W. Gryder and R. W. Dodson, *J. Chem. Phys.* 18, 579 (1950).
45. L. Friedman and W. F. Libby, *J. Chem. Phys.* 17, 647 (1949).
46. D. Urch and R. Wolfgang, *J. Amer. Chem. Soc.* 83, 2982 (1961).
47. R. A. Odum and R. Wolfgang, *J. Amer. Chem. Soc.* 85, 1050 (1963).
48. M. Henschman and R. Wolfgang, *J. Amer. Chem. Soc.* 83, 2991 (1961).
49. H. Keller and F. S. Rowland, *J. Phys. Chem.* 62, 1373 (1959).
50. J. G. Kay, R. P. Malsan and F. S. Rowland, *J. Amer. Chem. Soc.* 81, 5050 (1959).
51. F. S. Rowland, C. M. Wai, C. T. Ting and G. Miller, "Chemical Effects of Nuclear Transformations I", I.A.E.A., Vienna, 1965, p. 333.
52. Y. Y. Su and H. J. Ache, *J. Phys. Chem.* 80, 659 (1976).
53. G. F. Palino and F. S. Rowland, *Radiochim. Acta* 15, 57 (1971).
54. C. M. Wai and F. S. Rowland, *J. Phys. Chem.* 74, 434 (1970).
55. S. H. Daniel, H. J. Ache and G. Stöcklin, *J. Amer. Chem. Soc.* 78, 1043 (1974).
56. P. R. Geissler and J. E. Willard, *J. Phys. Chem.* 67, 1675 (1963).
57. R. J. Abraham and E. Bretschneider, "Rotational Isomerism", W. J. Orville-Thomas, ed., John Wiley and Sons, New York, 1974, chapter 13.
58. C. P. Smyth, "Dielectric Behavior and Structure", McGraw-Hill Book Co., Inc., New York, 1955.

59. R. J. Abraham, "The Analysis of High Resolution NMR Spectra", Elsevier, Amsterdam, 1971.
60. R. J. Abraham, M. A. Cooper, T. M. Siverns, F. F. Swinton, H. G. Weder and L. Cavalli, *Org. Mag. Resonance* 6, 331 (1974).
61. E. G. Claeys, G. P. Van der Kelen and Z. Eeckhaut, *Bull. Soc. Chim. Belg.* 70, 462 (1961).
62. H. B. Thompson, *J. Chem. Educ.* 43, 66 (1966).
63. E. L. Eliel, Private Communication.
64. B. Atkinson and M. Stedman, *J. Chem. Soc.*, 512 (1962).
65. M. E. Berg, W. M. Grauer, R. W. Helton and E. P. Rack, *J. Phys. Chem.* 79, 1327 (1975).
66. M. D. Loberg, K. A. Krohn and M. J^o Welch, *J. Amer. Chem. Soc.* 95, 5596 (1973).
67. K. C. To, M. E. Gerg, W. M. Grauer and E. P. Rack, *J. Phys. Chem.* 80, 1411 (1976).
68. R. G. Manning and J. W. Root, *J. Phys. Chem.* 79, 1478 (1975).
69. R. G. Manning and J. W. Root, *J. Chem. Phys.* 64, 4926 (1976).
70. G. Stöcklin, "Hot Atom Chemistry Status Report", I.A.E.A., Vienna, 1975, p. 161.
71. H.J. Ache, J.L. Wu, *J. Amer. Chem. Soc.* in press (1977).
72. P. Sppan, *J. Chem. Soc. A*, 3125 (1968).
73. O. Sinanoglu, "Molecular Associations in Biology", B. Pullman, ed., Academic Press, New York, 1968, p. 427.
74. L. Onsager, *J. Amer. Chem. Soc.* 58, 1486 (1936).
75. R. C. Weast, ed., "Handbook of Chemistry and Physics", 51st Edition, The Chemical Rubber Co., 1971.

XII. APPENDIX A

Computer program used to simplify a radioactivity graph where two peaks may overlap or tail into each other. The calculation assumes that the radioactivity of the isotope is specific, so the radioactivity graph must parallel the gas chromatogram.

When a peak appears on the gas chromatogram, the peak is collected at one minute intervals and counted. The counts for the one minute collection is proportional to the mass of the sample eluted. The area under the peak of the gas chromatogram is proportional to the mass of sample; therefore, the gas chromatogram is also broken up into matching one minute intervals. By dividing the area of the one minute collection into the counts for that interval, the total counts for the peak can be calculated. Each one minute interval gives an estimate of the total counts for a peak and overlapping or tailing is occurring when the total counts of the peak do not match the estimated total counts from the one minute intervals.

```

DIMENSION B(60),SA(3),CH(60),FRAC(60),XC(60),VAL(60),C(60)
INTEGER A(60)
C
C   READ THE NUMBER OF PEAKS
C   LOOP OVER PEAKS AND READ THE NUMBER OF POINTS IN EACH PK.
C   READ COLLECTION TIMES INTO ARRAY A AND COUNTS INTO ARRAY B
C
    READ(5,10)NPKS
    READ(5,10)NPTS
    CALL NEWPAG
    WRITE(6,14)
    14  FORMAT('*****',/, '*** NEW DATA SET ***',/, '*****')
        NPKS=NPKS-1
        READ(5,15)(A(I),I=1,NPTS)
        READ(5,55)(B(I),I=1,NPTS)
    55  FORMAT(7F10.5)
    10  FORMAT(I2)
    15  FORMAT(20I3)
    19  FORMAT(2I2)
        WRITE(7,410)
        WRITE(6,410)
    410 FORMAT(/, ' INPUT THE BACKGROUND')
C
C   THE BACKGROUND COUNTS IS INPUT INTERACTIVELY
C   AND CORRECT THE COUNTS
C   THEN CALCULATE THE COUNTS AT TIME 'ZERO'
C   B(K)=C(K)*EXP(-K*T) NOW SOLVE FOR C(K)
C   DK=K IS THE DECAY CONSTANT, THE TIME IS STORED IN A(K)=TA
C
    READ(8,55)BKGRD
    DO 25 J=1,NPTS
    B(J)=B(J)-BKGRD

```

```

TOB00010
TOB00020
TOB00030
TOB00040
TOB00050
TOB00060
TOB00070
TOB00080
TOB00090
TOB00100
TOB00110
TOB00120
TOB00130
TOB00140
TOB00150
TOB00160
TOB00170
TOB00180
TOB00190
TOB00200
TOB00210
TOB00220
TOB00230
TOB00240
TOB00250
TOB00260
TOB00270
TOB00280
TOB00290
TOB00300
TOB00310
TOB00320

```

```

25  CONTINUE
    DK=.01863
    DO 30 K=1,NPTS
    TA=FLUAT(A(K))
    C(K)=B(K)*EXP(DK*TA)
30  CONTINUE
    WRITE(6,34)
34  FORMAT(' TIME',5X,' COUNTS ',13X,' COUNTS T=0 ')
    WRITE(6,35)(A(II),B(II),C(II),II=1,NPTS)
35  FORMAT(1X,13,3X,G20.10,3X,G20.10)
C
C  READ THE MASS ELUTED BY THE CHROMATOGRAPH DURING A (ONE MINUTE)
C  TIME INTERVAL INTO ARRAY CH(I)
C  SUM CH(I) TO OBTAIN THE TOTAL MASS ELUTED
C  CONVERT THE MASS MEASUREMENTS TO FRACTIONAL UNITS
C
    READ(5,55)(CH(KK),KK=1,NPTS)
    TREA=0.0
    DO 70 KK=1,NPTS
    TREA=TREA+CH(KK)
70  CONTINUE
    DO 75 KK=1,NPTS
    FRAC(KK)=CH(KK)/TREA
    VAL(KK)=0.
    IF(FRAC(KK).GT..00001)VAL(KK)=C(KK)/FRAC(KK)
75  CONTINUE
    WRITE(7,89)
89  FORMAT(4X,' FRACTION ',8X,' RAW DATA ',9X,' JJ')
    DO 85 JJ=1,NPTS
    WRITE(7,90)FRAC(JJ),VAL(JJ),JJ
85  CONTINUE
90  FORMAT(' ',2X,G20.10,2X,G20.10,2X,13)

```

TOB00330
 TOB00340
 TOB00350
 TOB00360
 TOB00370
 TOB00380
 TOB00390
 TOB00400
 TOB00410
 TOB00420
 TOB00430
 TOB00440
 TOB00450
 TOB00460
 TOB00470
 TOB00480
 TOB00490
 TOB00500
 TOB00510
 TOB00520
 TOB00530
 TOB00540
 TOB00550
 TOB00560
 TOB00570
 TOB00580
 TOB00590
 TOB00600
 TOB00610
 TOB00620
 TOB00630
 TOB00640

```

C
C   SUM THE CORRECTED COUNTS UNDER EACH PEAK AND TAKE THE RATIO
C   OF THE RATIO OF THIS SUM FOR THE PEAKS
C
C   100  FORMAT(' INPUT CORRECTED TOTAL COUNTS ')
        WRITE(7,300)
        300  FORMAT(/,' INPUT INITIAL & FINAL POINTS 2I2 ')
C
C   INPUT THE INITIAL AND FINAL PTS. FOR EACH PEAK AND SUM THE COUNTS
C   UNDER THE PEAK
C   THEN INPUT (INTERACTIVELY) AN ESTIMATE THE TOTAL COUNTS UNDER EACH
C   PEAK AND CORRECT THE COUNTS
C
C   READ(8,19)INIT,NFIN
        SUM=0.
        DO 600 KK=INIT,NFIN
            SUM=SUM+C(KK)
        600  CONTINUE
            WRITE(7,610)SUM
            WRITE(6,610)SUM
        610  FORMAT(/,' THE SUMMED COUNTS IS ',G20.10)
            WRITE(7,100)
        READ(8,95)FACTOR
        DO 110 KK=1,NPTS
            XC(KK)=FACTOR*FRAC(KK)
        110  CONTINUE
            WRITE(6,120)
        120  FORMAT(' CORRECTED COUNTS ')
            WRITE(6,155)(XC(KK),KK=1,NPTS)
        155  FORMAT(6(2X,G10.5))
        95   FORMAT(G20.10)
            AREA=0.
        TOB00650
        TOB00660
        TOB00670
        TOB00680
        TOB00690
        TOB00700
        TOB00710
        TOB00720
        TOB00730
        TOB00740
        TOB00750
        TOB00760
        TOB00770
        TOB00780
        TOB00790
        TOB00800
        TOB00810
        TOB00820
        TOB00830
        TOB00840
        TOB00850
        TOB00860
        TOB00870
        TOB00880
        TOB00890
        TOB00900
        TOB00910
        TOB00920
        TOB00930
        TOB00940
        TOB00950
        TOB00960

```



```

DO 200 KK=1,NPTS
AREA=AREA+XC(KK)
200 CONTINUE
WRITE(6,355)AREA,FACTOR
355 FORMAT(/,' UNCORRECTED AREA= ',G20.10,' FACTOR= ',G20.10)
SA(NPKS+1)=AREA
IF(NPKS.GT.0)GO TO 13
RELA=SA(2)/SA(1)
IF(SA(2).LT.SA(1))RELA=SA(1)/SA(2)
WRITE(6,210) RELA,SA(1),SA(2)
210 FORMAT(' REL AREA ',G20.10,' AREA1 ',G20.10,' AREA2 ',G20.10)
STOP
END

```

```

TOB00970
TOB00980
TOB00990
TOB01000
TOB01010
TOB01020
TOB01030
TOB01040
TOB01050
TOB01060
TOB01070
TOB01080
TOB01090

```

XIII. APPENDIX B

Computer program used to calculate the individual dipole moments of conformers.

```

DIMENSION X(50),Y(50),Z(50),BM(50),BD(50)
DIMENSION BMX(50),BMY(50),BMZ(50),QX(50),QY(50)
C THIS PROGRAM CALCULATES DIPOLE MOMENTS FROM BOND MOMENTS
C AND CARTESIAN COORDINATES
C THETA IS IN DEGREES
C NUMDAT IS THE NUMBER OF DATASETS
C NBM IS THE NUMBER OF BOND MOMENTS
C FROM ATOM K TO ATOM L
C BM IS THE BOND MOMENT
  READ(1,10) NUMDAT
10  FORMAT(I2)
  READ(1,20) N
20  FORMAT(I3)
  READ(1,20) NBM
  READ(1,30)(X(I),Y(I),Z(I),I=1,N)
30  FORMAT(3(F8.4))
  DO 231 LL=1,N
  QX(LL)=X(LL)
  QY(LL)=Y(LL)
231  CONTINUE
  ITER=0
  DO 7000 IJKL=1,360
  THETA=FLOAT(IJKL)
  WRITE(6,414) THETA
414  FORMAT(2X,' THETA= ',F10.5)
  ITER=ITER+1
32  FORMAT(F8.4)
  CHI=THETA*3.1415/180.
  DO 33 KK=1,3
  KKK=5+KK
DIP00010
DIP00020
DIP00030
DIP00040
DIP00050
DIP00060
DIP00070
DIP00080
DIP00090
DIP00100
DIP00110
DIP00120
DIP00130
DIP00140
DIP00150
DIP00160
DIP00170
DIP00180
DIP00190
DIP00200
DIP00210
DIP00220
DIP00230
DIP00240
DIP00250
DIP00260
DIP00270
DIP00280
DIP00290
DIP00300
DIP00310
DIP00320

```

```

X(KKK)=COS(CHI)*QX(KKK)-SIN(CHI)*QY(KKK)
Y(KKK)=SIN(CHI)*QX(KKK)+COS(CHI)*QY(KKK)
CONTINUE
SUMX=0.
SUMY=0.
SUMZ=0.
DO 50 I=1,NBM
  IF(ITER.EQ.1)READ(1,40) K,L,BM(I)
  IF(ITER.EQ.1)WRITE(7) K,L,BM(I)
  IF(ITER.NE.1)READ(7) K,L,BM(I)
  40  FORMAT(2(I2,8X),F7.3)
  BD(I)=SQRT((X(L)-X(K))**2+(Y(L)-Y(K))**2+(Z(L)-Z(K))**2)
  35  FORMAT(' ',2(I2,8X),F8.4)
  BMX(I)=(X(L)-X(K))*BM(I)/BD(I)
  BMY(I)=(Y(L)-Y(K))*BM(I)/BD(I)
  BMZ(I)=(Z(L)-Z(K))*BM(I)/BD(I)
  SUMX=SUMX+BMX(I)
  SUMY=SUMY+BMY(I)
  SUMZ=SUMZ+BMZ(I)
  50  WRITE(6,60) SUMX,SUMY,SUMZ
  60  FORMAT(' ',3(F7.3,3X))
  DMOL=SQRT(SUMX**2+SUMY**2+SUMZ**2)
  70  WRITE(6,70) DMOL
  70  FORMAT('0','CALCULATED DIPOLE MOMENT ',F7.3,' DEBYES')
C
C  OPTION TO OBTAIN A PLOT OF THE GEOMETRY OF
C  THE SUBSTITUTED ETHANE
C
C  CALL NEWPAG
C  XIN=0.
C  YIN=0.
C  IF(ITER.EQ.1)XIN=3.

```

DIP00330
DIP00340
DIP00350
DIP00360
DIP00370
DIP00380
DIP00390
DIP00400
DIP00410
DIP00420
DIP00430
DIP00440
DIP00450
DIP00460
DIP00470
DIP00480
DIP00490
DIP00500
DIP00510
DIP00520
DIP00530
DIP00540
DIP00550
DIP00560

DIP00570
DIP00580
DIP00590
DIP00600

```

IF(ITER.EQ.1)YIN=3.
C CALL PLOT(XIN,YIN,-3)
C DO 100 II=1,N
C IF(II.NE.1.AND.II.NE.2)GO TO 91
C CALL SYMBOL(X(II),Y(II),.25,1HC,0.,1)
C GO TO 100
C 91 IF(II.NE.5.AND.II.NE.6)GO TO 92
C CALL SYMBOL(X(II),Y(II),.25,1HF,0.,1)
C GO TO 100
C 92 IF(II.NE.8.AND.II.NE.3)GO TO 93
C CALL SYMBOL(X(II),Y(II),.25,1HV,0.,1)
C GO TO 100
C CALL SYMBOL(X(II),Y(II),.25,1HH,0.,1)
C 93 CONTINUE
C 100 CONTINUE
C CALL PLOT(0.,0.,-4)
REWIND 7
CONTINUE
7000 CONTINUE
1000 CONTINUE
STOP
END
DIP00610
DIP00620
DIP00630
DIP00640
DIP00650
DIP00660
DIP00670
DIP00680
DIP00690
DIP00700
DIP00710
DIP00720
DIP00730
DIP00740
DIP00750
DIP00760
DIP00770
DIP00780
DIP00790
DIP00800
DIP00810

```

**The vita has been removed from
the scanned document**

CHLORINE-38 FOR CHLORINE SUBSTITUTION IN GEOMETRIC
AND DIASTEREOMERIC COMPOUNDS: MECHANISM
AND STEREOCHEMISTRY

by

Tobias Ralph Acciani

(ABSTRACT)

In order to determine how solvents control the stereochemical course of the hot substitution reactions, the stereochemistry of the energetic ^{38}Cl for Cl was studied in diastereomeric 1,2-dichloro-1,2-difluoroethane and the geometric isomers of 1,2-dichlorohexafluorocyclobutane. In each system the conformer population was determined by NMR and dipole moment techniques. A comparison was made between the changes of the stereochemical course of the substitution reaction and the concentration and nature of the solvent.

The results presented in this investigation indicate that the stereochemical course of a hot atom substitution reaction is directly controlled by solvents participating in the de-excitation stabilization of excited compounds or in the relaxation process of intermediate radicals. This work also indicates that the nature of the solvent cage wall can control the progress of the hot reaction. Abstraction reactions of the Cl can occur in the cage with the compounds composing the cage wall. These reactions can effectively change the stereochemical course of the hot substitution

reaction.

It appears that the liquid phase hot atom substitution reactions observed in this investigation are best explained by the caged radical-radical combination model. Strong solute-solvent interactions reduce the time for relaxation of the radicals in the solvent cage thus preventing the radicals from obtaining planarity and consequently retention products. On the other hand, weak solute-solvent interactions increase the time for relaxation of the intermediate which leads to a racemization of reaction products.