

AN INVESTIGATION OF
THE LONG-RANGE PROTON PERFLUOROMETHYL
AND FLUORINE PERFLUOROMETHYL COUPLINGS
IN 2,5-DIFLUORO-
AND 3,4-DIFLUOROBENZOTRIFLUORIDE

A Thesis
Submitted to
The Faculty of Graduate Studies and Research
at the University of Manitoba
in Partial Fulfillment
of the Requirements for the Degree of
MASTER OF SCIENCE

by
WALTER P. NIEMCZURA

Winnipeg, Manitoba

August, 1976

"AN INVESTIGATION OF
THE LONG-RANGE PROTON PERFLUOROMETHYL
AND FLUORINE PERFLUOROMETHYL COUPLINGS
IN 2,5-DIFLUORO-
AND 3,4-DIFLUOROBENZOTRIFLUORIDE"

by

WALTER P. NIEMCZURA

A dissertation submitted to the Faculty of Graduate Studies of
the University of Manitoba in partial fulfillment of the requirements
of the degree of

MASTER OF SCIENCE

© 1976

Permission has been granted to the LIBRARY OF THE UNIVER-
SITY OF MANITOBA to lend or sell copies of this dissertation, to
the NATIONAL LIBRARY OF CANADA to microfilm this
dissertation and to lend or sell copies of the film, and UNIVERSITY
MICROFILMS to publish an abstract of this dissertation.

The author reserves other publication rights, and neither the
dissertation nor extensive extracts from it may be printed or other-
wise reproduced without the author's written permission.

FOR KIFFORD

ACKNOWLEDGEMENTS

I would like to thank Dr. T. Schaefer for the help and advice he gave me during the past two years.

I am also indebted to Drs. C. M. Wong and T.-L. Ho. Without their guidance, I would still be synthesizing the samples studied.

Special thanks are also due Dr. W. J. E. Parr and Mr. K. Chum for assistance in using the computer programs necessary for this work and to Drs. L. J. Kruczynski and R. Wasylshen for the many helpful discussions we engaged in over the last two years.

Last, but not least, I sincerely thank my wife Margo for all the time she devoted to correcting and typing this manuscript and for enduring me over the past two years.

I am grateful to the Chemistry Department of the University of Manitoba for financial assistance.

ABSTRACT

Two compounds, 2,5-difluorobenzotrifluoride and 3,4-difluorobenzotrifluoride, were synthesized so that the long-range coupling in these compounds could be studied. Spectral analysis yielded the shifts and all the coupling constants, but particular attention was directed towards the H,CF₃ and F,CF₃ long-range coupling constants. Spin decoupling and tickling experiments were performed; and ${}^4J_{\text{O}}^{\text{F,CF}_3}$, ${}^5J_{\text{m}}^{\text{F,CF}_3}$, and ${}^6J_{\text{p}}^{\text{F,CF}_3}$ were all found to be positive with respect to ${}^3J_{\text{O}}^{\text{F,F}}$ and/or ${}^5J_{\text{p}}^{\text{F,F}}$. The observed substituent dependence of ${}^4J_{\text{O}}^{\text{H,CF}_3}$ in the compounds studied and in others appearing in the literature is qualitatively discussed while the substituent dependence of ${}^5J_{\text{m}}^{\text{H,CF}_3}$ is noted but not discussed. Calculations using the INDO-MO-FPT method of Pople were performed for various orientations of the perfluoromethyl group with respect to the aromatic plane. The calculated couplings reported include ${}^4J_{\text{O}}^{\text{H,CF}_3}$ for both compounds; ${}^5J_{\text{m}}^{\text{H,CF}_3}$ for both compounds; ${}^6J_{\text{p}}^{\text{H,CF}_3}$, ${}^4J_{\text{O}}^{\text{F,CF}_3}$, ${}^5J_{\text{m}}^{\text{F,CF}_3}$ for both compounds; and ${}^6J_{\text{p}}^{\text{F,CF}_3}$. The five- and six-bond F,CF₃ couplings are discussed, with the aid of the calculated data, with regard to the roles of the σ -mechanism and the σ - π exchange mechanism in transmitting these couplings. ${}^4J_{\text{O}}^{\text{F,CF}_3}$, which is transmitted by the through-space mechanism, is discussed and compared with existing experimental and theoretical data.

TABLE OF CONTENTS

	<u>Page</u> <u>No.</u>
I. INTRODUCTION.	1
A. The Origins of Internuclear Magnetic Interactions . . .	2
B. Perturbation Theory: The Average Energy Approximation.	5
C. Extension of the Theory to Non-Directly Bonded Nuclei	8
II. THEORY.	12
A. Coupling Through Sigma Bonds.	13
B. Coupling Through Pi Bonds	21
C. Recent Work Concerning Fluorine-Fluorine Couplings. .	25
1. General Fluorine-Fluorine Couplings	26
2. Through-Space Couplings	31
D. Determination of the Sign of Coupling Constants . . .	34
1. Absolute Signs of Coupling Constants in Aromatic Systems.	35
2. Double or Multiple Resonance.	37
III. NATURE OF THE PROBLEM	40
IV. EXPERIMENTAL METHOD	42
A. Samples	42
B. NMR Method.	45
V. EXPERIMENTAL RESULTS.	49
A. 2,5-Difluorobenzotrifluoride.	50
B. 3,4-Difluorobenzotrifluoride.	65

TABLE OF CONTENTS (Continued)

	<u>Page No.</u>
VI. DISCUSSION.	73
A. Long-Range Couplings.	74
1. Introduction.	74
2. Long-Range Couplings in Aromatic Systems.	75
a. Ring Proton Couplings	75
b. Coupling Between Ring and Methyl Protons.	81
c. Coupling Between Ring and Methyl Protons and Other Nuclei	86
d. Coupling Between Perfluoromethyl and Ring Protons.	89
e. Coupling Between Perfluoromethyl and Ring Fluorines.	99
B. Through-Space Couplings	105
1. Introduction.	105
2. Through-Space Couplings in Aromatic Systems	107
VII. SUMMARY AND CONCLUSIONS	112
VIII. RECOMMENDATIONS FOR FUTURE RESEARCH	114
BIBLIOGRAPHY.	115
APPENDIX A.	122
APPENDIX B.	127

LIST OF FIGURES

<u>Figure No.</u>		<u>Page No.</u>
2.1	Contributing valence bond structure for a generalized bond fragment.	16
2.2	Orbital representation of H,H coupling through the butanic fragment	17
2.3	Major canonical structures to the singlet and triplet states of s-cis-1,4-difluorobutadiene.	31
2.4	Arrangement of the progressive and regressive energy levels	39
5.1	Experimental and calculated 100 MHz proton spectra of 2,5-difluorobenzotrifluoride.	52
5.2	Experimental and calculated 56.4 MHz fluorine spectra of F-2 in 2,5-difluorobenzotrifluoride	53
5.3	Experimental and calculated 56.4 MHz fluorine spectra of F-5 in 2,5-difluorobenzotrifluoride	54
5.4	Experimental and calculated 56.4 MHz fluorine spectra of the perfluoromethyl group in 2,5-difluorobenzotrifluoride	55
5.5	Experimental and calculated 60 MHz proton spectra of 2,5-difluorobenzotrifluoride	56
5.6	Stick plot used for interpreting the partial decoupling experiments	58
5.7	Result of the partial decoupling experiment performed on 2,5-difluorobenzotrifluoride.	59
5.8	Energy level diagram used for interpreting the tickling experiments	61
5.9	Results of the tickling experiments performed on 2,5-difluorobenzotrifluoride	62
5.10	Experimental and calculated tickling experiments for 2,5-difluorobenzotrifluoride	63
5.11	Experimental and calculated 100 MHz spectra of 3,4-difluorobenzotrifluoride	66
5.12	Experimental and calculated 56.4 MHz fluorine spectra of F-3 in 3,4-difluorobenzotrifluoride	67

LIST OF FIGURES (Continued)

<u>Figure No.</u>		<u>Page No.</u>
5.13	Experimental and calculated 56.4 MHz fluorine spectra of F-4 in 3,4-difluorobenzotrifluoride	68
5.14	Experimental and calculated 56.4 MHz fluorine spectra of the perfluoromethyl group of 3,4-difluorobenzotrifluoride	69
5.15	Results of the spin tickling experiment performed on 3,4-difluorobenzotrifluoride	70
5.16	Experimental and calculated spin tickling experiments for 3,4-difluorobenzotrifluoride	72
6.1	Diagrammatic representation of the interaction between a nuclear spin and an electron spin in a $2p_z$ orbital in an aromatic system	76
6.2	Diagrammatic representation of the coupling between protons through the π -electron network of toluene.	82
6.3	A plot of the calculated values of ${}^4J_{H,CF_3}$ vs θ for 2,5-difluorobenzotrifluoride	95
6.4	A plot of calculated values of ${}^5J_{H,CF_3}$ and ${}^6J_{H,CF_3}$ vs θ for 2,5-difluorobenzotrifluoride	97
6.5	A plot of calculated values of ${}^5J_{F,CF_3}$ and ${}^6J_{F,CF_3}$ vs θ for 3,4-difluorobenzotrifluoride	101
B-1	The double resonance Hamiltonian matrix for the general ABC spin system.	129

LIST OF TABLES

<u>Table No.</u>		<u>Page No.</u>
5.1	NMR spectral parameters for 2,5-difluorobenzotrifluoride and 3,4-difluorobenzotrifluoride. . . .	51
6.1	Initial and final values of the H,H couplings in 2,5-difluoro- and 3,4-difluorobenzotrifluoride . . .	78
6.2	A comparison of values of ${}^4J_{O}^{H,CF_3}$ observed in several compounds.	90
6.3	Calculated values of ${}^4J_{O}^{H,CF_3}$ for various orientations of the CF_3 group in 2,5-difluoro- and 3,4-difluorobenzotrifluoride	94
6.4	Calculated values of ${}^5J_{m}^{H,CF_3}$ and ${}^6J_{p}^{H,CF_3}$ for various orientations of the CF_3 group ^P in 2,5-difluoro- and 3,4-difluorobenzotrifluoride	96
6.5	Calculated values of ${}^5J_{m}^{F,CF_3}$ and ${}^6J_{p}^{F,CF_3}$ for various orientations of the CF_3 group ^P in 2,5-difluoro- and 3,4-difluorobenzotrifluoride	100
6.6	Calculated values of ${}^4J_{O}^{F,CF_3}$ for various orientations of the CF_3 group in 2,5-difluorobenzotrifluoride using CNDO/2 and INDO.	110
B-1	Allowed transitions in the A region for the double resonance AMX system	131

I. INTRODUCTION

This work is concerned with the theory and the experimental determination of the electron-transmitted spin-spin coupling constants between fluorine nuclei on the side chain and fluorine nuclei or protons on the ring in two benzotrifluoride derivatives. The following pages will be biased in that there is no discussion concerning the chemical shifts of the nuclei in the molecules studied. The shifts are reported as determined through spectral analysis, but their significance with regard to their molecular environment is not of interest here. The reader is referred to some of the standard references and review articles for information concerning this topic.¹

Ever since the first observation of field-independent splittings of the nuclear magnetic resonance peaks in liquids in 1951,^{2,3} spin-spin coupling constants have been the subject of intensive research. Due to the subtle dependence of this internuclear interaction on molecular configuration and conformation and on electronic environment, this parameter has become a sensitive probe into the structure of atoms and molecules. From the hyperfine splittings measured in radicals and paramagnetic species to the spin-spin couplings observed in organic compounds in solution, both experiment and theory have been presented to exemplify and explain these phenomena.

A. The Origins of Internuclear Magnetic Interactions

Even in the absence of an external magnetic field, a magnetic nucleus will be affected by the presence of other proximate magnetic moments. The other moments will contribute to a small local magnetic field at the site of this nucleus. These effects are manifested as line broadening in solids and as hyperfine structure in the spectra of radicals and organic molecules in solution. The broadening is due to direct spin dipole-dipole interactions. The dipole-dipole interaction is generally anisotropic; and in solution where the molecules undergo rapid tumbling, this interaction is averaged to zero. The hyperfine structure in the spectra of diamagnetic species arises from the interaction between nuclear spins transmitted via the magnetic polarization of the intervening molecular electrons.

Ramsey and Purcell⁴ first formulated the origin of these interactions on a theoretical basis. The theory, later refined by Ramsey,⁵ evaluated the energy of these interactions on the basis of second order perturbation theory. The expression of the coupling energy can be written as

$$E_{AB} = \sum_n \frac{\langle 0 | H' | n \rangle \langle n | H' | 0 \rangle}{E_0 - E_n} \quad -1.1-$$

$|0\rangle$ and $|n\rangle$ represent the ground state and excited state wave functions of the molecule, respectively, with energies E_0 and E_n . The summation in Eq. 1 is over all excited states including those of the continuum. The Hamiltonian in Eq. 1 has the form⁵

$$H' = H^{1a} + H^{1b} + H^2 + H^3 \quad -1.2-$$

where H^{1a} and H^{1b} are the orbital terms and are given by

$$H^{1a} = \frac{e\hbar\beta}{c} \sum_{N,N',k} \gamma_N \gamma_{N'} r_{kN}^{-3} r_{kN'}^{-3} [(\underline{I}_N \cdot \underline{I}_{N'}) (\underline{r}_{kN} \cdot \underline{r}_{kN'}) - (\underline{I}_N \cdot \underline{r}_{kN'}) (\underline{I}_{N'} \cdot \underline{r}_{kN})] \quad -1.3-$$

and

$$H^{1b} = \frac{2\beta\hbar}{i} \sum_{N,k} \gamma_N r_{kN}^{-3} \underline{I}_N \cdot (\underline{r}_{kN} \times \nabla_k) \quad -1.4-$$

where β is the Bohr magneton, γ_N and $\gamma_{N'}$ are the magnetogyric ratios of nuclei N and N' having nuclear spins \underline{I}_N and $\underline{I}_{N'}$, respectively, and \underline{r}_{kN} is the radius vector connecting electron k and nucleus N . These terms represent the magnetic shielding of the direct nuclear interaction by the electron orbital motions.

The term H^2 is given by

$$H^2 = 2\beta\hbar \sum_{N,k} \gamma_N [3(\underline{S}_k \cdot \underline{r}_{kN}) (\underline{I}_N \cdot \underline{r}_{kN}) r_{kN}^{-5} - (\underline{S}_k \cdot \underline{I}_N) r_{kN}^{-3}] \quad -1.5-$$

where \underline{S}_k is the spin of electron k . This term evaluates the dipole-dipole interaction between the nuclear magnetic moments and the magnetic moments of the electrons.

Finally, the H^3 term is

$$H^3 = \frac{16\pi\beta\hbar}{3} \sum_{N,k} \gamma_N \delta(\underline{r}_{kN}) \underline{S}_k \cdot \underline{I}_N \quad -1.6-$$

where $\delta(\underline{r}_{kN})$ is the Dirac delta function and is present to restrict H^3 to operating on wave functions only at the nucleus.

The H^3 term is usually referred to as the "contact" term and was first suggested by Fermi⁶ in 1930 to explain the hyperfine structure in atomic spectra. Until recently, this Hamiltonian has been the starting point for two main approaches to the calculation of spin-spin coupling. The first and most widely used approach has its basis in perturbation theory and was first developed by Ramsey.⁵ The other method used is the variation method. Although the latter procedure eliminates some of the difficulties encountered in perturbation theory (e.g. the infinite summation in Eq. 1.1), it presents some serious difficulties even for simple molecules.⁷ It has been pointed out that, depending on assumptions made, the two approaches lead to similar expressions for the coupling. The approaches to perturbation theory will be briefly reviewed first, followed by a look at their applications to different coupling situations.

B. Perturbation Theory: The Average Energy Approximation

Ramsey first used his formulation to calculate the coupling in the HD molecule. He was able to show, using perturbation theory, that the coupling constant $J_{NN'}$, between nuclei N and N' has the form

$$J_{NN'} = J_{NN'}^{1a} + J_{NN'}^{1b} + J_{NN'}^2 + J_{NN'}^3 \quad -1.7-$$

In his work, he demonstrated that about 90% of the coupling between protons arises from $J_{NN'}^3$. Cross terms involving the separate components of the Hamiltonian are either zero, too small to consider, or average to zero during frequent tumbling in solution. $J_{NN'}^3$ can be expressed as*

$$J_{NN'}^3 = \frac{-2}{3h} \left(\frac{16\pi\beta\hbar}{3} \right)^2 \gamma_N \gamma_{N'} \sum_n \left[\frac{\langle 0 | \sum_k \delta(\underline{r}_{-kN}) S_{-k} | n \rangle \langle n | \sum_j \delta(\underline{r}_{-jN'}) S_{-j} | 0 \rangle}{E_n - E_0} \right] \quad -1.8-$$

where, again, the first summation is over the ground state and all excited states. Complete knowledge of all the excited state wave functions, even for the simplest of molecules, is not available; and this summation presents a formidable obstacle to the rigorous calculation of an exact value of this term.

*Further discussions will consider only $J_{NN'}^3$, where this term offers the major contribution to the coupling. $J_{NN'}^{1a}$, $J_{NN'}^{1b}$, and $J_{NN'}^2$ are generally subject to the same approximations that are applied to $J_{NN'}^3$. For details concerning the exact form of the other terms in Eq. 1.7, the reader is referred to the original work⁵ or the review of Barfield and Grant.⁸

Here Ramsey invoked the average energy approximation through the closure theorem which substitutes a term $\Delta E^{(i)}$ for each of the $(E_n - E_0)$ terms in Eq. 1.7. The $\Delta E^{(i)}$'s are evaluated with respect to the value of the matrix elements for each excited state. In general, since each matrix element is different for the operators in Eq. 1.7, the $\Delta E^{(i)}$ terms must be specified for each mechanism. Using this approximation, Eq. 1.8 can be written as

$$J_{NN'}^3 = \frac{-2}{3h} \left(\frac{16\pi\beta\hbar}{3} \right)^2 \frac{\gamma_N \gamma_{N'}}{\Delta E^{(3)}} \left(\langle 0 | \sum_{k,j} \delta(\underline{r}_{kN}) \delta(\underline{r}_{jN'}) \underline{S}_k \cdot \underline{S}_j | 0 \rangle \right) \quad -1.9-$$

Unfortunately, a precise evaluation of the $\Delta E^{(3)}$ term is as difficult as evaluating the coupling constant itself. Because of this, various amounts of empiricism are inherent in the perturbation approach to spin-spin couplings. For example, a series of compounds might be studied where the $\Delta E^{(i)}$'s are expected to remain relatively constant. Any change in the coupling constant is then attributed to minor changes in the molecular wave function.

Working with the James and Coolidge wave function for H_2 , Ramsey chose a $\Delta E^{(3)}$ value to yield a calculated contribution from $J_{NN'}^3$ in HD of 40 Hz, reasoning that the other terms in Eq. 1.7 would contribute less than 3 Hz to the coupling. His estimate of $\Delta E^{(3)}$ was not completely arbitrary but is similar to values used at that time in the theoretical calculations of other magnetic interactions. Since the time of this initial work, both the variational procedure⁹ and perturbation theory¹⁰ have been applied to both valence bond (VB) type and molecular orbital (MO) type wave functions in the evaluation of

couplings between directly bonded nuclei. Barfield and Grant⁸ have pointed out some trends for each of these approximate wave functions. They observed that the completely covalent VB wave functions tend to give values on the high side of the experimental coupling while the values from the more ionic MO functions were considerably lower than the experimental value. They also noted three important factors involved in the calculation of spin-spin coupling constants. These are:

- (1) the effective nuclear charge,
 - (2) hybridizational contribution of orbitals,
- and
- (3) the spacial correlation of the electrons at the two coupled nuclei.

Although these points were made concerning coupling between directly bonded nuclei, their effect has been felt throughout the whole of coupling theory.

C. Extension of the Theory to Non-Directly Bonded Nuclei

Even though Ramsey's theory was initially used to describe the couplings between directly bonded nuclei, his formulation proved to be a useful starting point for the calculation of interactions through a varying number of intervening atoms. The accuracy of these calculations is hampered by the various degrees of approximation in the wave functions used to represent molecules. Despite these limitations, recent formulations have experienced considerable success in predicting magnitudes and experimentally observed trends. This section will attempt briefly to summarize this work, pointing out the assumptions used and similarities in the respective formulations.

McConnell¹¹ first applied Ramsey's formulation to molecular orbital theory. In his work, McConnell employed a closed shell single determinant wave function of the form

$$\psi_0 = \left[\frac{1}{\sqrt{2^M}} \right] \left(\psi_1(1)\alpha(1)\psi_1(2)\beta(2)\cdots\psi_M(2M-1)\alpha(2M-1)\psi_M(2M)\beta(2M) \right) \quad -1.10-$$

where $\psi_1, \psi_2, \dots, \psi_M$ denote doubly occupied LCAO (Linear Combination of Atomic Orbitals) molecular orbitals and have the form

$$\psi_i = \sum_j c_{ij} \phi_j \quad -1.11-$$

Using these wave functions, McConnell obtained the following expression for the contact term:

$$J_{NN'} = \frac{1}{4h} \left(\frac{16\pi\beta\hbar}{3} \right)^2 \gamma_N \gamma_{N'} (\Delta E)^{-1} \phi_N^2(0) \phi_{N'}^2(0) |P_{NN'}|^2 \quad -1.12-$$

where $\phi_N^2(0)$ and $\phi_{N'}^2(0)$ are the squares of the magnitudes of the atomic

orbitals at nuclei N and N' and

$$P_{NN'} = 2 \sum_i^{\text{occ}} c_{iN} c_{iN'} \quad -1.13-$$

the c_{iN} terms referring to the atomic orbital coefficients in the molecular orbitals. This expression is analogous to a bond order between nuclei N and N'. This correlation necessarily predicts a positive coupling, whereas interactions of both sign are known.

Pople and Santry^{12,13} later refined this approach by replacing the $P_{NN'}$ term with one of the form

$$\pi_{NN'} = \frac{\partial P_{NN'}}{\partial \alpha_N} = 4 \sum_i^{\text{occ}} \sum_j^{\text{unocc}} \frac{c_{iN} c_{iN'} c_{jN} c_{jN'}}{E_i - E_j} \quad -1.14-$$

where the summations are over the occupied and unoccupied molecular orbitals of the system. This term is a measure of the mutual atom-atom polarizability and can have either sign. Even with this correction, some of their predicted positive couplings (e.g. $J_{\text{gem}}(\text{H,H})$ and $J(^{13}\text{C-C-H})$) are known experimentally to be negative. Their formulation, however, correctly predicts the effect of electronegative substituents on geminal H,H couplings.¹⁴

A further advance was later made by Pople and his co-workers.¹⁵ Working only with the Fermi contact term, they evaluated a set of unrestricted self-consistent field molecular orbitals (SCFMO). In this formulation, electrons of different spin occupy two different sets of MO's and are not paired in the same MO's, as was the conventional practice. The procedure applies a finite perturbation (FP) at one of