

イミダクロプリドおよび関連化合物の光安定性に関する量子 化学的考察

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Original Article

Quantum Chemical Consideration of Photostability of Imidacloprid and Related Compounds

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The electronic configurations in ground and excited states of imidacloprid and related compounds were obtained by AM1 and *ab-initio* methods. The evaluated energy gap from the ground state to the singly excited state (S1) is in order of cyanoimine > nitroimine > nitromethylene, which is in accord with the actual photostability order among these compounds. Judging from that the HOMOs reside mostly in the guanidino or amidino part comprising the imidazolidine nitrogens and the LUMOs stretch toward the nitro and cyano groups, the primary excitations by UV absorption of these molecules is classified as the intramolecular donor-acceptor electron transfer. To this context more electron-donating thiazolidine exhibits a bathochromic shift from the imidazolidine compounds. The nitro group is coplanar with the guanidino or amidino part in the ground states. In the triplet excited state (T1) the nitro group becomes twist from the plane in the nitroamide, on the other hand in the nitroimine the distortion is to such a small degree as the resonance stability can be still expected. The energy gap between HOMO and LUMO, and the bonding nature in the excited states are the determining factor for the photolytic behavior of chloronicotiny molecules on field.

INTRODUCTION

Imidacloprid (**1**), 6-chloronicotiny-2-nitroiminoimidazolidine, is the first commercial product of a new class of insecticide named as chloronicotiny or neonicotiny insecticides which act as agonists on the nicotinic acetylcholine receptors.¹⁻⁹⁾ It was reported that there were dozens candidates equally active for commercial development at the stage of greenhouse tests, and imidacloprid was finally selected above all based on its superior results in field tests in addition to its intrinsic activity.¹⁰⁻¹⁴⁾ In order to trace the determining criteria for its favorable environmental behavior we studied recently the relationships between the structure and the physicochemical parameters associated with weathering conditions for more than thirty chloronicotiny molecules of different skeletons and with a variety of functional groups, and found that the photostability is a crucial factor for the selection.¹⁵⁾ Molecules comprising nitroimine or cyanoimine structure turned out to be more stable than nitromethylene analogs under the sunlight. In principle the photostability in the field should be ascribed to the favorable molecular absorption properties

within the sunlight wavelength range. In this paper we sought the origin of the different absorption features depending on the structural elements of the molecules listed in Fig. 1 in the light of quantum chemistry, and found that the phenomena could be accounted for by a conventional AM1 method.

METHODS

All of quantum chemical calculations were implemented by a semi-empirical molecular orbital program package (MOPAC ver. 6.01), with AM1-Hamiltonian,¹⁶⁾ unless otherwise stated. The optimized structure of the individual molecular species was used to obtain the stable conformation in the ground state (S0) and to calculate the electronic parameters. As for the singlet excited states (S1) and triplet excited states (T1), both of the unchanged geometry during the transition (Franck-Condon geometry) and the optimized vibrational states were calculated. The UV absorption wavelengths (λ_{\max} ; nm) can be obtained by the following equation,

$$\lambda_{\max} = 28,635 / (E_{S1} - E_{S0})$$

where E_{S1} and E_{S0} are the respective SCF energy (kcal/mol) for S0 and S1 states in Franck-Condon geometries.¹⁷⁾ The bond orders and bond energies for **1** and **2** in ground and excited states were obtained by

* Chloronicotiny Insecticides (Part 9). Part 8, see Ref. 24; Part 7, see Ref. 1.

using BONDS and ENPART options in MOPAC. Most stable conformation of **1** was obtained in a way as follows. Molecular models were constructed using standard bond lengths and angles. By rotating all single bonds stepwise by 60° , 36 sets of initial coordinates which contain the whole conformational space were generated, then all internal coordinates of each initial conformation were optimized by AM1 method and the most stable one was selected for discussion. The *ab-initio* Hartree-Fock calculations were carried out at STO-3G, 4-31G and 6-31G levels using GAMESS program.¹⁸⁾

RESULTS AND DISCUSSION

1. Conformation of Imidacloprid (**1**) in the Ground State

The AM1 calculation predicted that the most stable structure of imidacloprid should be composed of the collinear π -conjugation network from the imidazolidine

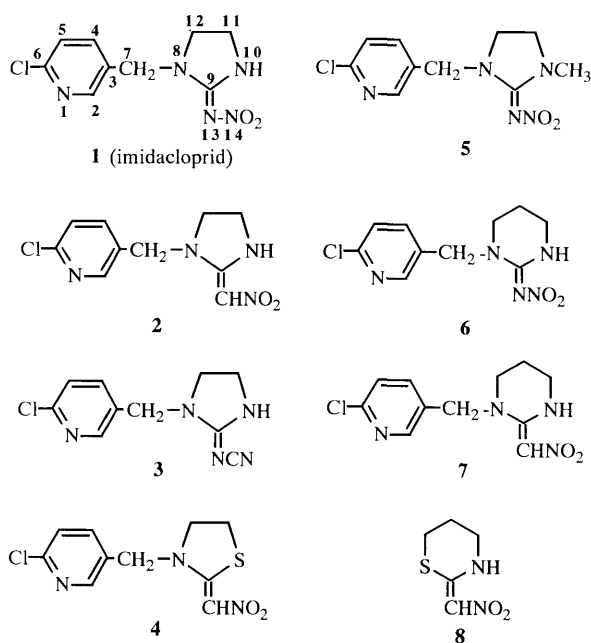


Fig. 1 Imidacloprid and related compounds.

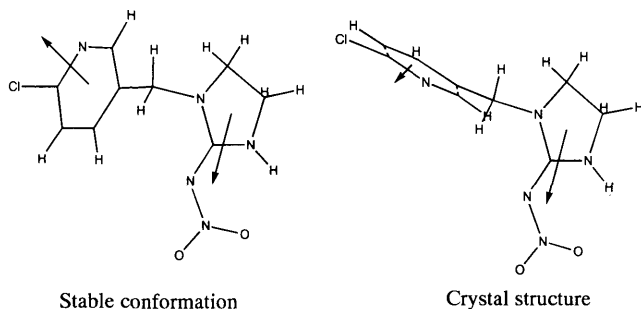


Fig. 2 An estimated stable conformation for **1** and the crystal structure which is 2.87 kcal/mol higher in energy than the estimated, and the direction of the dipolar vectors for each molecule.

part to the nitroimino group and of the C=N bond of *E*-geometry to be able to form an intramolecular hydrogen bonding ($\text{NO}_2 \cdots \text{HN}$) (Fig. 2). These features are in accord with the actual crystal structure.¹⁹⁾ A difference lies in the conformation of the molecule with respect to the orientation of the imidazolidine ring to the pyridine rings. In the crystal the both ring planes are almost perpendicular with each other through the methylene spacer (the dihedral angle of 3-7-8-9 is -93.08°), and the 2-hydrogen atom on the pyridine ring is closely above the imidazolidine nitrogen atom with the interatomic distance of 2.42 Å. This value is smaller than the van der Waals length (2.75 Å) of nonbonded N-H. In the most stable conformation the pyridine ring rotates by *ca.* 23° from the angle of the crystal structure (its dihedral angle of 3-7-8-9 is -69.18°) to release the steric repulsion amounting to 2.8 kcal/mol.

Another conspicuous difference is the dipolar vector of the molecule. In the stable rotamer the pyridyl and the nitroiminoimidazolidinyl parts are oriented in the opposite directions so as to set off the individual dipole moment each other. Such an orientation is reasonable from the viewpoint of molecular electrostatics because structures of smaller total dipole vectors in magnitudes are generally more stable in vacuum and in nonpolar solvents. In comparison, in the real crystal structure the both parts are oriented toward a direction to increase the total molecular vector. It has been stated that dipolar structures are generally favored in polar media or under specific intermolecular effects.²⁰⁾ In fact, the intermolecular hydrogen bonds as well as molecular stacking in the crystal structure of imidacloprid, $\text{NH} \cdots \text{O}_2\text{N}$ and $\text{NH} \cdots \text{N}$ (pyridine), have been reported in literature.¹⁹⁾

2. Frontier Orbitals and Electronic Excitation

1-Amino-2-nitroolefins show high-intensity bands ($\log \epsilon = 4.1-4.3$) due to $\pi-\pi^*$ transitions in the region longer than 350 nm.^{21,22)} The maximum absorption in a series of 1-substituted 2-nitroimino-2-imidazolidines occurs at 265–269 nm ($\log \epsilon = 4.1-4.3$).²³⁾ On the other hand, the absorption maxima of ordinary substituted pyridines are around 250 nm with intensities of $\log \epsilon = 3.3-3.5$.¹⁷⁾ Further judging from the conformational features discussed above, the replacement of the chloropicolyl group by a methyl group would not change the essential chromophore structure. We have hence compared the electronic properties of the original chloronicotinyl compounds **1-7** using the simple methyl derivatives for the economy of calculations. The *N*-methyl analogues are signified by an added cypher Me like **1-Me** and so on. The righteousness of our assumption was assured by calculation of the λ_{max} of *N*-methyl derivative **1-Me** yielding 258 nm close to 257 nm of **1**.

The frontier orbital shapes by AM1 method are schematically given in Fig. 3. The reliance on the AM1

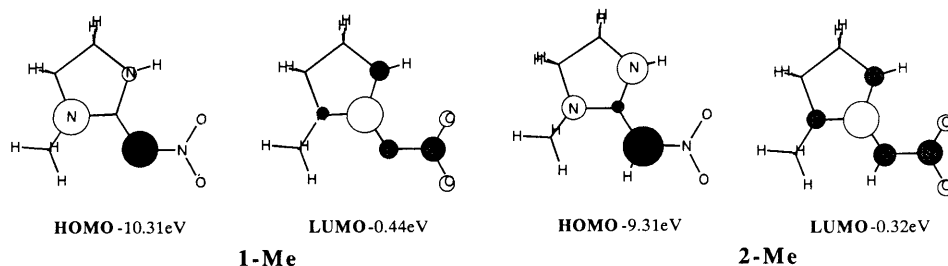


Fig. 3 Illustration of frontier orbitals of **1-Me** and **2-Me**.

The open and shadowed circles signify the opposite sign of the AO coefficient to each other, and its size is proportional to the magnitude of the coefficient.

calculation was confirmed by the similar tendency obtained by *ab-initio* method both at 4-31G and 6-31G levels.

The HOMOs reside mostly in the guanidino moiety in **1-Me** or the corresponding amidino part in **2-Me**, but a difference between them was observed in the orbital features of the C=X bond; the AO coefficient on the carbon atom is almost nil in **1-Me** while in **2-Me** the significant coefficient magnitude lies on the carbon. The LUMOs stretch toward the nitro groups in both cases. Hence judging from the frontier orbital shapes, the HOMO-LUMO transfer should be assigned to the intramolecular donor-acceptor transfer of the π -electrons from the guanidino or amidino part to the individual nitro group. The total Mulliken charges of the NO₂ and the guanidino parts in the S₀ states of **1-Me** were calculated to be -0.173 and -0.595 respectively, while those in the S₁ state were -0.280 and -0.474. This suggests the intramolecular electron transfer from the guanidino moiety to the nitro group during the S₀-S₁ transition. The similar electron transfer was estimated for molecule **2-Me** (the Mulliken charges in the NO₂ and amidino parts were -0.212 and -0.505 respectively in the S₀ state and those in the S₁ state were -0.280 and -0.332). The LUMO profiles of the both molecules are similar in respect that the C=N and C=C bonds are of antibonding character and the N-NO₂ and C-NO₂ bonds are of bonding.

3. Correlation between Absorption Spectrum and Molecular Structure

A rather simple AM1 where no configuration interactions are treated, nevertheless, reproduced well the longest wavelengths of **1-Me-7-Me** of the tendency of the actual absorptions of the chloronicotinyl molecules **1-7** (Table 1).

The far longer maximum wavelength of C=CHNO₂ (**2-Me**) than C=NNO₂ (**1-Me**) attributes evidently to the smaller energy gap between the ground state and the excited state; the HOMO/LUMO (eV) are -9.31/-0.32 (**2-Me**) and -10.31/-0.44 (**1-Me**). The primary photolysis of pesticide molecules on earth is caused by

Table 1 Observed electronic absorption of compounds **1-8** and the half-life times ($t_{1/2}$) by photolysis, and the calculated absorption maxima (λ_{\max}).

Compd.	$\lambda_{\max}/\log \epsilon$ ($\log \epsilon$ at 290 nm) ^{a)}	$t_{1/2}$ (hr) ^{b)}	calcd. λ_{\max} (nm) ^{c)}
1	269/4.17 (3.73)	3	258
2	323/4.09	1	305
3	268/3.56 (<0.01)	>24	252
4	357/4.23	<0.5	325
5	255/4.10 (2.85)	3.5	257
6	269/3.61 (3.21)	3.5	266
7	313/4.17	2	318
8	348/4.07	0.5	339

^{a)} The λ_{\max} (nm) and $\log \epsilon$ values were obtained in the aqueous solution using a UV spectrometer (UV-160, Shimadzu) at 25°C.¹⁵⁾

^{b)} The $t_{1/2}$ data were obtained by irradiation of the compound in acetonitrile-water (8:2, v/v) solution using a 250-W sun lamp (NC 7222 Sun Light Beam Lamp, National Elc.) at 30°C.¹⁵⁾

^{c)} $\lambda_{\max} = 28,635 / (E_{s1} - E_{s0})$. Calculations were carried out using the *N*-methyl derivatives **1-Me-7-Me** instead of 6-chloro-3-pyridylmethyl group of compounds **1-7**.

the sunlight of wavelength between 290 and 400 nm. As mentioned above the maximum wavelengths over *ca.* 290 nm of molecules **1**, **2** and **3** are contributed not by the chloronicotinyl group but by the amidino or guanidino chromophore. It is self-evident that nitromethylenyl amidine **2** absorbing strongly right in the middle of this range is rapidly decomposed, losing the intrinsic activity in the field, whereas derivatives **1** and **3**, bearing nitro- or cyanoguanidine chromophore with far shorter absorption maxima than 290 nm, have substantially longer half-lives. The maximum absorption wavelength of thiazolidinyl nitromethylene **4** are longer as large as 34 nm than **2**, and that of tetrahydrothiazine **8** is 25 nm longer, consequently the both molecules decay much more rapidly than **2**. It is also noteworthy that nitroimino compounds, **1**, **5** and **6**, have yet the tailing absorptions with pretty large $\log \epsilon$ values at 290 nm, while that value of cyanoimino compound **3** is almost nil. The much longer half-life of compound **3** than the former compounds is

obvious from these absorption differences (Table 1).

The evaluated lengths for **4-Me** and **8** are in accord well with the actual longer wavelengths of **4** and **8** than **2** and **7**. Since the absorption (S0-S1) is due to the intramolecular donor-acceptor electron transfer from the ring hetero atoms to the nitromethylenyl part, introduction of a soft atom having the higher HOMO like sulfur as the electron donator should cause a bathochromic shift. However, interestingly molecule **5** exhibits no bathochromic shift, though the enhanced mesomery effect could be expected by methylation on another imidazolidine nitrogen. This unusual phenomenon can be explained by the disrupted π -electron cascade by the steric constraints produced by the methylation. In our calculation the nitro group is twisted 44° from the C=X plane in **5-Me**, whereas the corresponding twist angle in **1-Me** is only 11° . These calculated data measure up to the crystal structure of compound **5** where the nitro group tips out of the guanidine plane to a right angle.²⁴⁾ Actually **5** has a significantly longer half-life than **1**.

For the six-membered ring compounds, nitroimine (**6-Me**) and nitromethylene (**7-Me**), their wavelengths calculated by a semi-empirical method were longer than the corresponding five-membered rings, **1-Me** and **2-Me**, contrary to the observed results with the corresponding chloronicotiny derivatives. Further the wavelength values for the five-membered compounds as a whole are likely to be calculated smaller by 10–30 nm than the observed (distorted molecule **5-Me** is the exception whose calculated value was coincided with the observed). These deviation may be ascribed to the limited accuracy by the AM1 method using the empirical integration terms. We have therefore examined *ab initio* on the precise geometries. The calculation at STO-3G and 4-31G levels showed that the imidazolidine nitrogen atoms are not pyramidal (sp^3 configuration) as predicted by the AM1 but trigonal (sp^2 configuration) (Fig. 4). This means that these heteroring nitrogens are not of amine but imine in nature, and that the lone pair electrons on these nitrogen atoms move toward the nitroimine or nitromethylene part. These results are

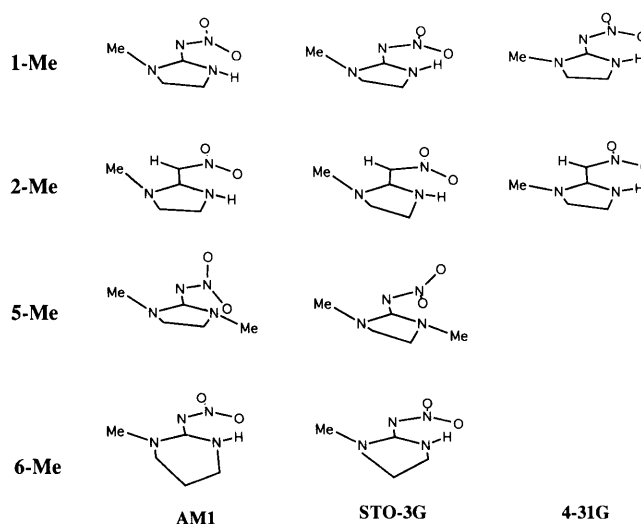


Fig. 4 Stable conformations of **1-Me**, **2-Me**, **5-Me** and **6-Me** calculated by semi-empirical and *ab-initio* methods. Each column represents the calculation methods.

consistent with the crystal structures of **1** and **2** obtained by X-ray analysis, where the N-C=X parts are planar.²⁴⁾ The shorter wavelengths of these molecules are the consequence of the lowered HOMO levels of the individual nitrogen atom induced by the π -electron delocalization.

As for the six-membered ring compounds, **6-Me** and **7-Me**, not only the *ab-initio* calculation at the higher levels but also the AM1 method predicted the trigonal configuration of the N-C=X parts, affording the reasonable values for them.

Next we looked at the bond orders and the bond energies in Franck-Condon states for **1-Me** and **2-Me** (Table 2). Interestingly, the C=N bond order in **1-Me** increases notably during the intersystem crossing from S1 to T1 even to a higher degree than in the ground state, while in **2-Me** the bonding order in T1 becomes lower considerably than S1 and much more than S0. We examined the optimized structures to compare the result of the different bonding nature in the excited states. It turned out that in **2-Me** the nitro group tips from the

Table 2 Bond orders and energies of **1-Me** and **2-Me** in the ground and excited states.

Compd.	State	C=X		X-NO ₂		$E_{tot}^{c)}$
		Bond order ^{a)}	$E_{bond}^{b)}$	Bond order ^{a)}	$E_{bond}^{b)}$	
1-Me	S0	1.467	-20.50	0.937	-15.38	—
	S1	1.161	-17.93	1.007	-14.72	110.97
	T1	1.502	-20.23	0.907	-14.64	70.25
2-Me	S0	1.521	-21.42	0.950	-16.98	—
	S1	1.067	-17.44	1.028	-15.93	93.74
	T1	0.981	-16.46	0.936	-15.17	47.65

^{a)} Estimated by BONDS option of MOPAC.

^{b)} Bond energy (kcal/mol) estimated by ENPART option of MOPAC.

^{c)} Total excitation energy (kcal/mol).

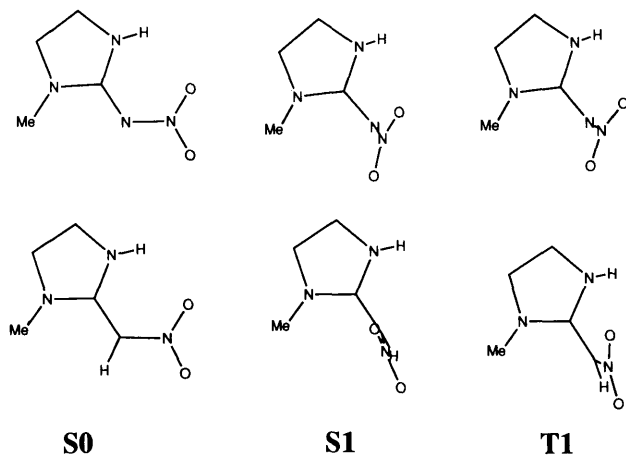


Fig. 5 Stable conformations of **1-Me** (upper row) and **2-Me** (lower row) in S0, S1 and T1 states.

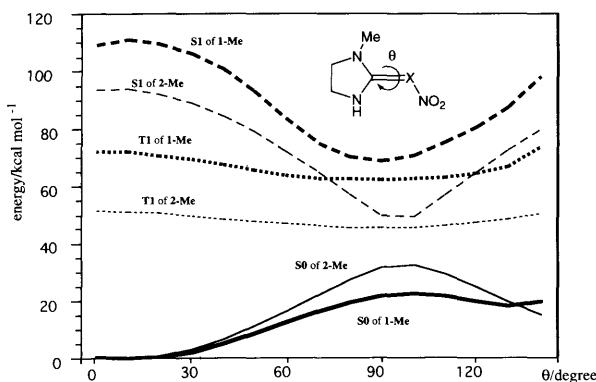


Fig. 6 Energy profiles plotted as a function of the rotational angle along the C=X axis θ for **1-Me** and **2-Me** in each state.

amidino plane significantly in the T1 state, in contrast with **1-Me** where the nitro group is only slightly deviated from the guanidino plane so that the conjugation facility can be still expected (Fig. 5). From these energetic characteristics we suppose that **1** should not decay through a biradical process so readily as does **2**.

In order to examine the fate of the excited molecules more in detail, we have traced the energy profiles in the S0, S1 and T1 states for **1-Me** and **2-Me** as the function of the rotational angle along the C=X axis (θ) while keeping the other internal coordinate elements constant (Fig. 6). The minimum potentials of S1 and the potential of T1 come clearly closer for the both molecules. It is therefore plausible that singly excited species of **1-Me** and **2-Me** decay readily to the T1 states through intersystem crossing after the structural relaxation.

In conclusion, the AM1 and *ab-initio* calculations grounded for the better photostability of **1** than **2** by, 1) the larger excitation energy (S0-S1) of **1** and, 2) the still expected bonding nature in the C=X bond of **1** in the excited states.

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要 約

イミダクロプリドおよび関連化合物の光安定性に関する量子化学的考察

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イミダクロプリドと関連化合物の基底状態と励起状態を AM1 法や *ab-initio* 法で求めた。シングレット励起状態 (S1) のエネルギー差はニトロメチレン < ニトロイミン < シアノイミンの順序であり、ニトロメチレン誘導体の容易な光分解性を裏づけた。HOMO は主としてイミダゾリジン環上窒

素原子を含むグアニジンやアミジン部位に存在し、LUMOはニトロ基やシアノ基まで広がっていることから、紫外線吸収により π 電子が供与体から受容体に遷移することがわかった。したがって、イミダゾリジン誘導体より電子供与性のチアゾリジン誘導体が長波長にシフトする。ニトロ基とアミジンあるいはグアニジン部位とはいずれも基底状態では共平面上にあるが、トリプレット励基状態 (T1) に

おいてニトロアミジンではニトロ基が共平面から大きくねじれるのに対して、ニトロイミンではほぼ共平面性が保たれるため、T1においても後者の二重結合性が十分に保持されることが予測される。以上のように、HOMO-LUMOのエネルギー差と励基状態での結合強度の差がニトロメチレン、ニトロイミノそしてシアノイミノ基を含むクロロニコチニル系殺虫剤分子の圃場での光安定性を決定している。