Interaction of *Trans*-Retinol And 1,1-Diamino-2,2-Dinitroethylene (FOX-7)-A DFT Treatment

Lemi Türker

Middle East Technical University, Department of Chemistry Üniversiteler, Eskişehir Yolu No:1, 06800
Çankaya/Ankara, TURKEY

lturker@gmail.com, lturker@metu.edu.tr

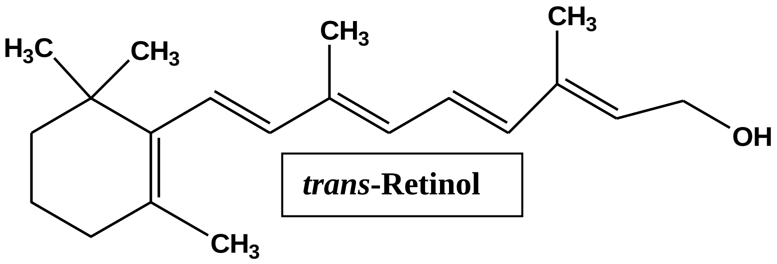
Abstract:

trans-Retinol is a highly conjugated molecule whose oxidized form *trans*-retinal has prime importance in the metabolism of vision. On the other hand, 1,1-diamino-2,2-dinitroethylene (FOX-7) is a pull-push type insensitive explosive material. The present study considers the interaction between *trans*-retinol and FOX-7 molecules at the level of B3LYP/6-31+G(d). Some structural, quantum chemical and spectral properties are obtained for the *trans*-retinol and FOX-7 composite. The calculations indicate that the mode of interaction in the composites of *trans*-retinol and FOX-7 in one hand and *trans*-retinal and FOX-7, on the other hand, is different. In the case of *trans*-retinol, possibly some orbital interactions happen with FOX-7 additionally.

Keywords: Retinol, Vitamin A, FOX-7, DADNE, Explosive, DFT.

1. Introduction

Retinol (Vitamin A) is a fat-soluble vitamin that belongs to a family of similarly shaped molecules, the retinoids, and occurs in several chemical forms, notably an aldehyde (retinal), alcohol (retinol), and an acid (retinoic acid). In foods of animal origin, the major form of vitamin A is an ester, primarily retinyl palmitate, which is converted to retinol. Precursors to the vitamin (provitamins) are present in foods of plant origin as some of the members of the carotenoid family of compounds [1]. It is readily available from a diversity of both plant and animal matter. Vitamin A is an essential human nutrient for normal metabolic functioning in both the embryo and the adult, including normal cell growth and development and vision [2]. In the metabolism of vision all-*trans*-retinol is converted to 11-*cis*-retinol[2]. Vitamin A actually refers to a family of similarly shaped molecules: The retinoids. The basic structure of the retinoid molecule consist of a cyclic end group, a polyene side chain, and a polar end group. The conjugated system formed by alternating C=C double bonds in the polyene side chain is responsible for the color of retinoids (typically yellow, orange, or red). Hence, many retinoids are chromophores. Alternation of side chains and end groups creates the various classes of retinoids [2]. The important part of vitamin A is the retinyl group, which can be found in several forms.



The discovery of vitamin A stemmed from research dating back to 1906, indicating that factors other than carbohydrates, proteins, and fats were necessary to keep cattle healthy [3]. By 1917, one of these substances was independently discovered by Elmer McCollum at the University of Wisconsin-Madison, and Lafayette Mendel and Thomas Osborne at Yale University. Since "water-soluble factor B" (Vitamin B) had recently been discovered, the researchers chose the name "fat-soluble factor A" (vitamin A) [3]. Vitamin A was first synthesized, in 1947, by two Dutch chemists, David Adriaan van Dorp, and Jozef Ferdinand Arens.

FOX-7 (1,1-diamino-2,2-dinitroethylene, diaminodinitroethylene, DADNE) was synthesized in 1998 by researchers of the Swedish Defense Research Agency (FOI) [4,5]. Since then, its explosive potential has been thoroughly investigated [6-20]. FOX-7 is a novel high-energy insensitive material which possesses good thermal stability and low sensitivity. It exhibits excellent application performance among the known insensitive ammunitions and solid propellants. FOX-7, although its structure and molecular composition are simple, exhibits abundant and surprising chemical reactivity (including coordination reactions, nucleophilic substitutions, electrophilic addition reactions, acetylate reactions, oxidizing and reduction reactions, etc., [21,22]). It is due to the presence of amino and nitro groups in its structure.

2. Method of Calculations

Initially, MM2 method was employed for the structure optimizations leading to energy minima. Then, semi-empirical PM3 self-consistent fields molecular orbital (SCF MO) method [23,24] at the restricted level [25,26] was used. Subsequent optimizations were achieved at Hartree-Fock level by using various basis sets. Then, the optimizations were managed within the framework of density functional theory (DFT) using B3LYP functional [27,28] at the level of B3LYP/6-31+G(d). The exchange term of B3LYP consists of hybrid Hartree–Fock and local spin density (LSD) exchange functions with Becke's gradient correlation to LSD exchange [28,29]. The correlation term of B3LYP consists of the Vosko, Wilk, Nusair (VWN3) local correlation functional [30] and Lee, Yang, Parr (LYP) correlation correction functional [31]. Also, the vibrational analyses were done at the same level of calculations employed for the optimizations. The total electronic energies (E) are corrected for the zero point vibrational energy (ZPE) to yield E_c values. The normal mode analysis for each structure yielded no imaginary frequencies for the $3N-6$ vibrational degrees of freedom, where N is the number of atoms in the system. This indicates that the structure of each molecule corresponds to at least a local minimum on the potential energy surface. All these calculations were done by using the Spartan 06 package program [32].

3. Results and Discussion

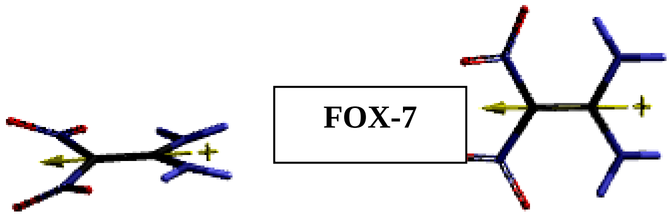
FOX-7 molecule has electron donor amino groups and electron acceptor nitro groups

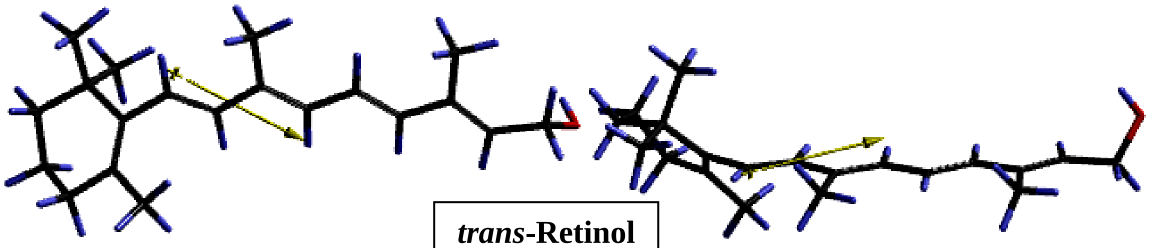
oriented in such a way that a pull-push type system arises. It has a dipole moment of 8.66 D (calc.).

On the other hand, trans-retinol possesses an endocyclic double bond but four trans double bonds constituting highly conjugated molecular system. The three methyl groups along the conjugated path are inductively electron donors. Note that endocyclic double bond may also be in conjugation with the unsaturated side moiety.

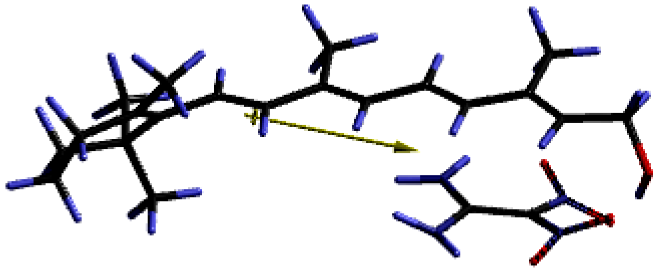
When FOX-7 and *trans*-retinol systems are in the vicinity of each other, main factors of interaction might be charge-charge, dipole-dipole, charge-dipole even the orbital interactions.

Figure 1 shows the systems considered presently. The notation, *trans*-retinol+FOX-7, stands for the composite system of *trans*-retinol and FOX-7. The figure also displays the direction of the dipole moment vectors. In the composite, the positive tail of the dipole moment vector resides on the retinol moiety, and the head aims at FOX-7. Thus, indicating the donor and acceptor components.





***trans*-Retinol**



***trans*-Retinol+FOX-7**

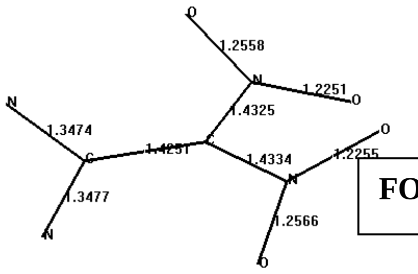
Figure 1. Optimized structures of the chemical systems considered (from different angles of view).

As seen in the figure, the NO_2 groups of FOX-7 molecule prefer to orient themselves nearby the carbinol part of the retinol system. Possibly, a hydrogen bonding forms. The shortest distance between O-H and NO_2 oxygen is 2.078 Å. Figure 2 shows the calculated bond lengths of the optimized structures considered.

The bond lengths of the composite system (*trans*-retinol+FOX-7) are different from the respective bond lengths of each component.

Figure 3 shows the charges (ESP) on the atoms of the species considered (Hydrogens not shown). Note that ESP charges are obtained by the program based on a numerical method that generates charges that reproduce the electrostatic field from the entire wave function [32]. As seen in Figure 3, the charges on the respective atoms of each component are different from they are in the composite.

Figure 4 shows the calculated IR spectra of the systems considered. As seen in the figure, the spectrum of the composite differs from the spectrums of the components in terms of positions and intensities of the peaks as well as some missing and additional peaks.



FOX-7

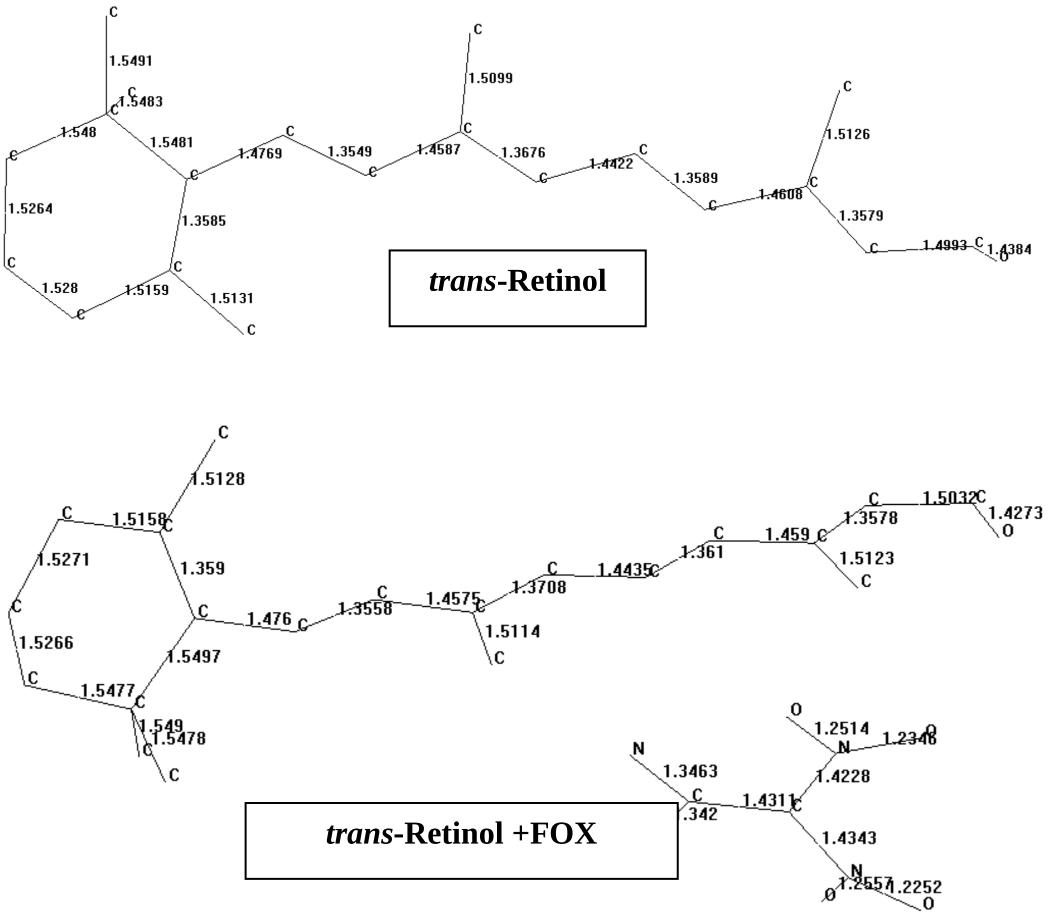
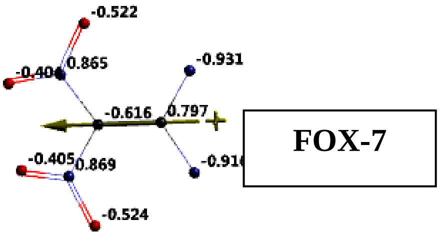
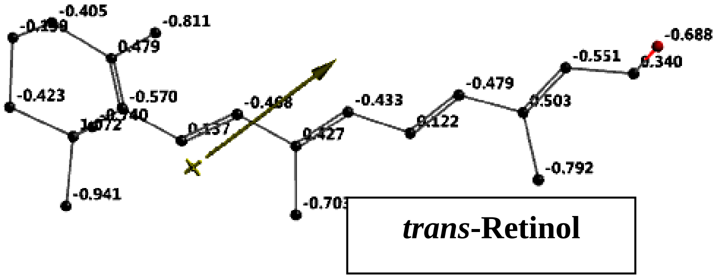


Figure 2. Calculated bond lengths of the optimized structures considered (Hydrogens not shown).





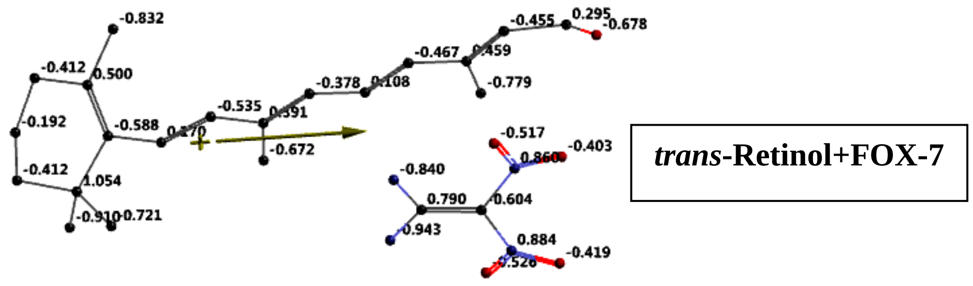


Figure 3. ESP charges on the atoms of the spcies considered (Hydrogens not shown).

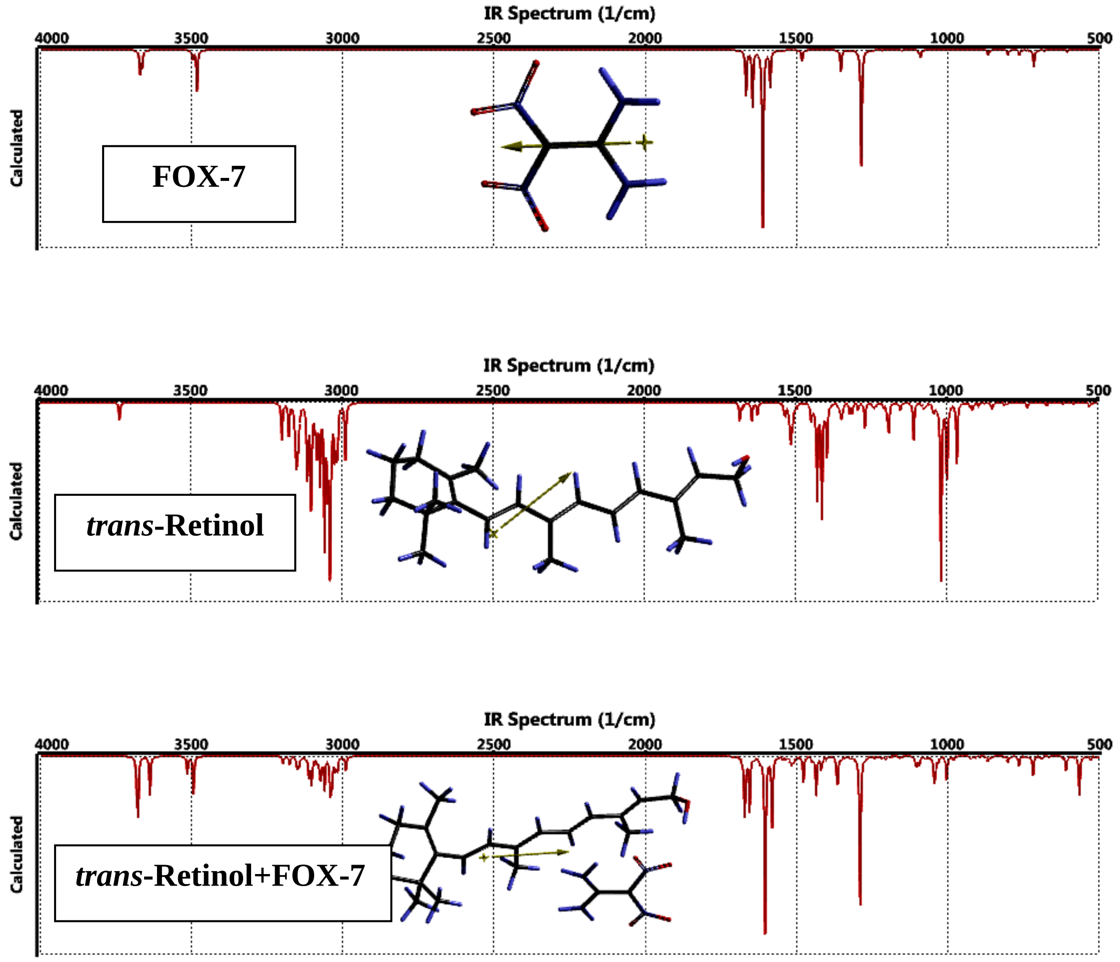


Figure 4. Calculated IR spectra of the species considered.

Table 1 shows various energies of the systems considered where E, ZPE, and E_c stand for the total electronic energy, zero point vibrational energy and ZPE corrected total electronic energy, respectively.

Table 1. Various energies of the systems considered.

System	E	ZPE	E_c
FOX-7	-1570947.81	241.57	-1570706.24
***trans*-Retinol**	-2245823.53	1191.68	-2244631.85
***trans*-Retinol+FOX-7**	-3816795.88	1438.46	-3815357.42

Energies in kJ/mol.

Note that the sum of E_c values of FOX-7 and *trans*-retinol is -3815338.08 kJ/mol., whereas the respective value of the composite is -3815357.42 kJ/mol., which indicates that some stabilization exists in forming the composite system. On the other hand, using the information included in Table 2, ΔG°_{reac} for the composite formation is +47.95528 kJ/mol. Thermodynamically the composite formation is not favorable (at the standard conditions) which might be due to the unfavorable entropy change (-237 J/mol) accompanying the composite formation.

System	H° (kJ/mol.)	S° (J/mol°)	G° (kJ/mol.)
FOX-7	-1570696.349	373.83	-1570807.808
***trans*-Retinol**	-2244597.167	589.24	-2244772.851
***trans*-Retinol+FOX-7**	-3815316.229	726.07	-3815532.703

Figure 5 displays the UV-VIS spectra (time-dependent DFT) of the systems considered. The spectrum of the composite system indicates that interaction between the components is strong and causes a bathochromic effect associated with emerging of some extra peaks as compared to the components.

Table 3 and Figure 6 show some molecular orbital energy levels/energies of the systems considered. The information included in them indicates how the presence of components affects the molecular orbital energy levels in the composite considered. The NHOMO and HOMO energy levels of the composite are higher then the respective energy levels of FOX-7 but lower than the levels of *trans*-retinol. On the other hand, the NLUMO and LUMO energy levels in the composite are lower than the levels of FOX-7 and *trans*-retinol. Consequently, Δε values follow the order of composite < *trans*-retinol< FOX-7. The narrowing of interfrontier molecular orbital energy gap (Δε) [33] in the composite as compared to both of the components is a good indication for some sort of π-π type interaction between the components.

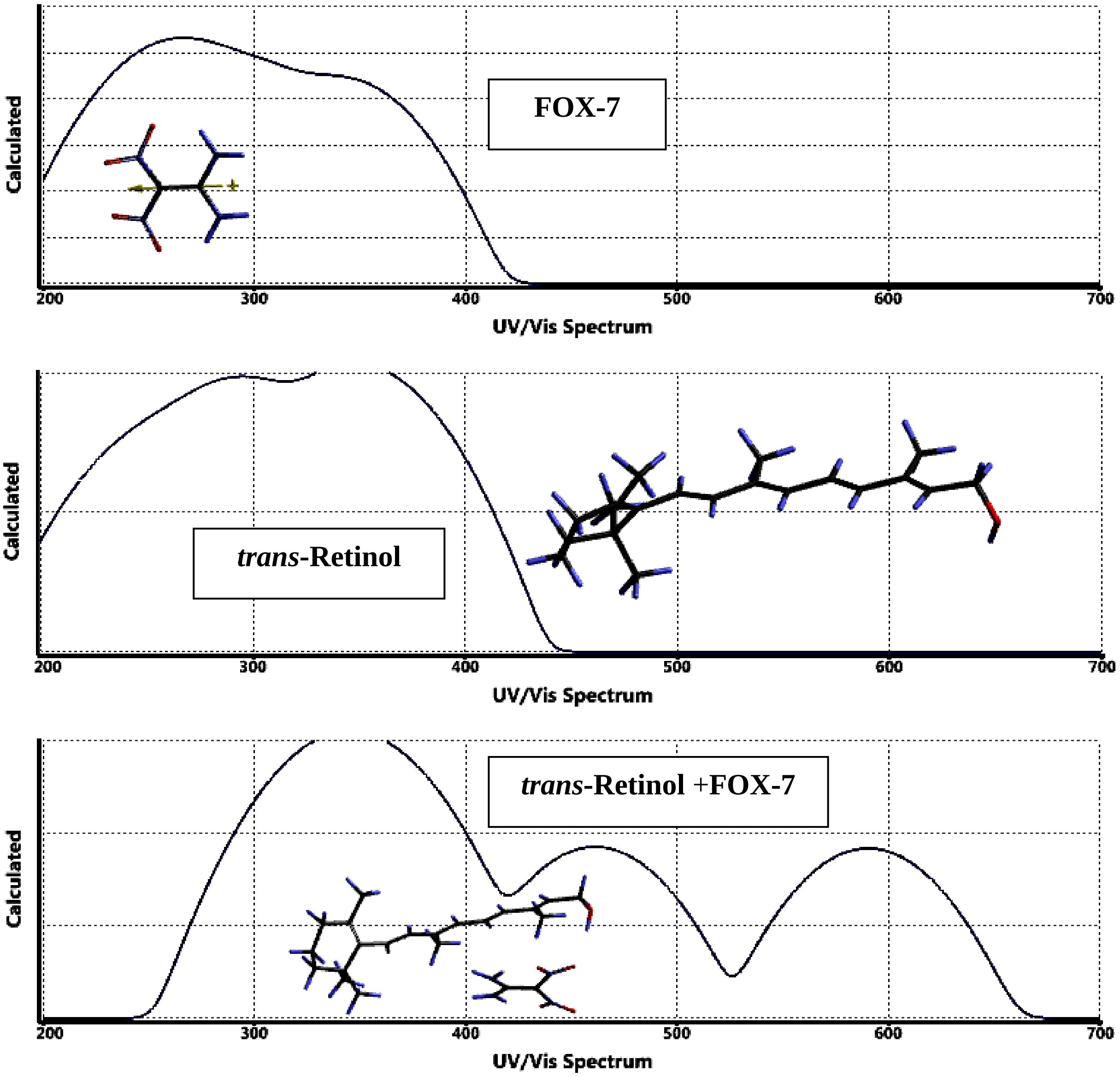


Figure 5. UV-VIS spectra of the species considered.

Table 3. Some molecular orbital energies of the systems considered.

System	NHOMO	HOMO	LUMO	NLUMO	Δε
FOX-7	-13.1682	-11.965	-4.57248	-3.75824	7.39248
***trans*-Retinol**	-10.2013	-8.44016	-3.02368	-0.51504	5.41648
***trans*-Retinol+FOX-7**	-10.6141	-8.91296	-4.78256	-3.78464	4.1304

All have A type symmetry. Energies in $*10^{-19}$ Joule.

As seen in Table 3 the energies/energy levels of the composite system are not simply embedded energies of the components. Thus the interaction between the components is not simply charge-charge, dipole-dipole or /and charge-dipole type but some orbital interactions occur.

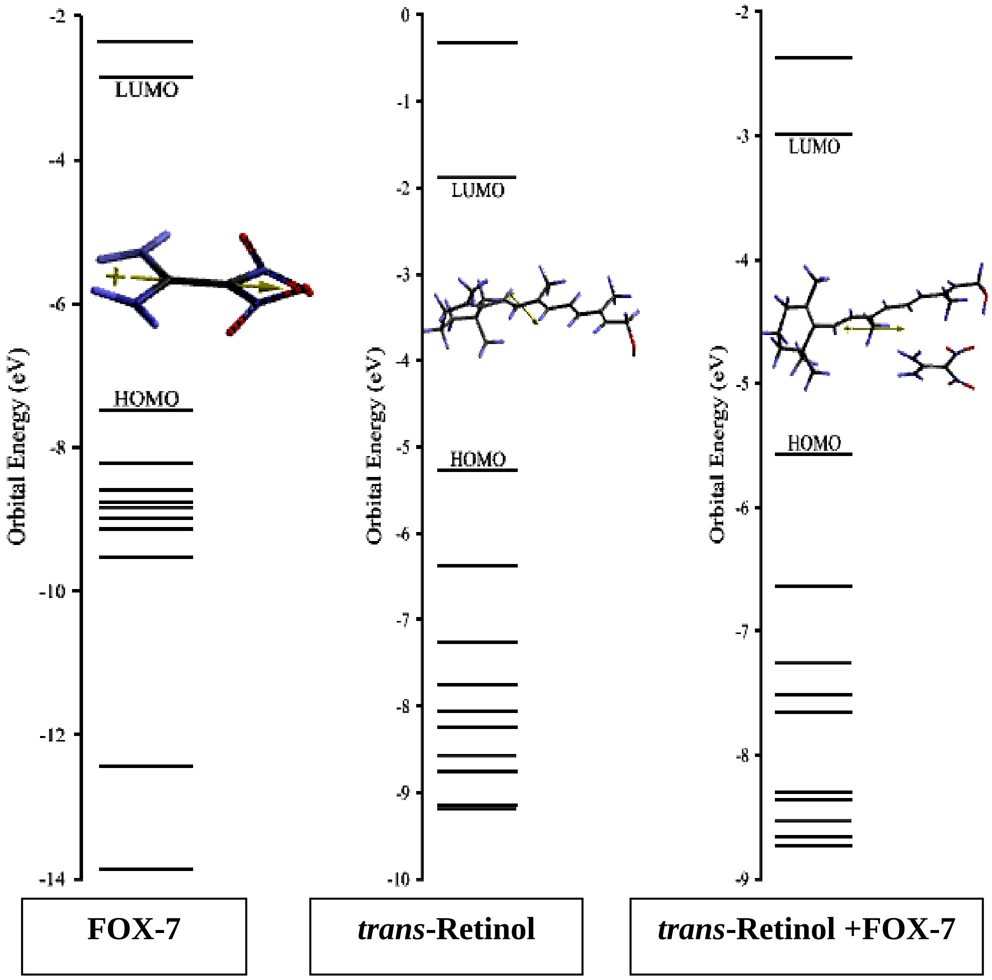
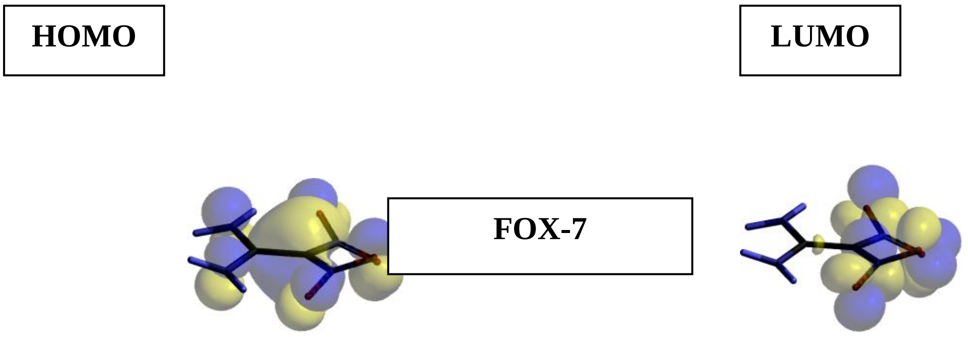
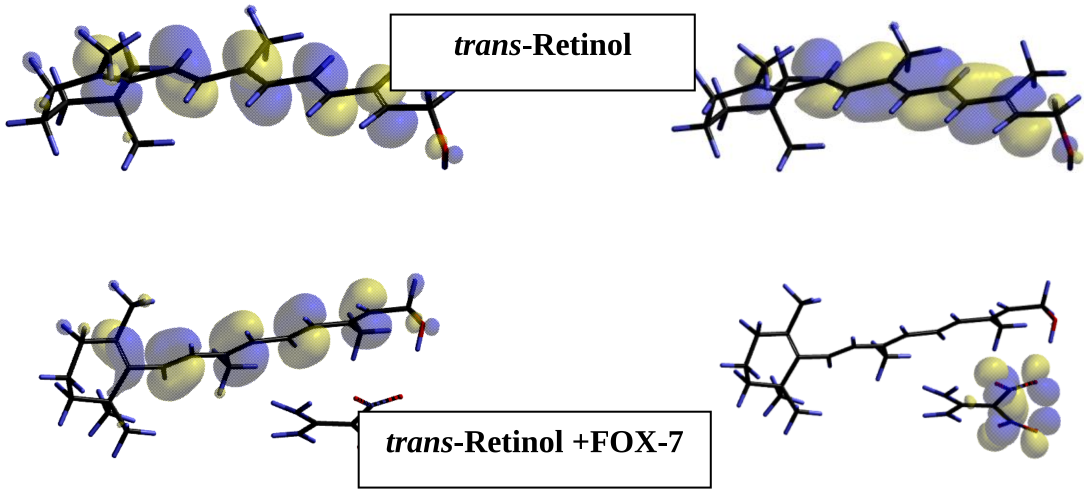


Figure 6. Some molecular orbital energy levels of the systems considered.

Figure 7 shows the HOMO and LUMO patterns of the systems considered, and indeed, orbital interactions are also evident from Figure 7, where in the composite system the HOMO spreads only over the retinol moiety, and the LUMO is supplied by FOX-7 moiety merely.

On the other hand, Figure 8 shows the optimized structure of *trans*-retinal+FOX-7 composite system obtained at the same level of calculation carried out for the *trans*-retinol +FOX-7 composite. As seen there, the mode of interactions in two composites is different. Note that in both composites, hydrogen bond formation possibility exists. Also, charge-charge, dipole-dipole and charge-dipole interactions are possible in different magnitudes. The orientation of the component molecules in *trans*-retinol +FOX-7 composite suggests orbital interactions additionally.





trans-Retinol

trans-Retinol +FOX-7

Figure 7. The HOMO and LUMO patterns of the systems considered.

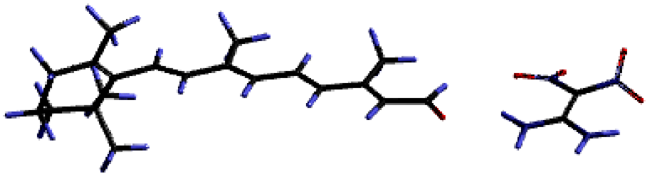
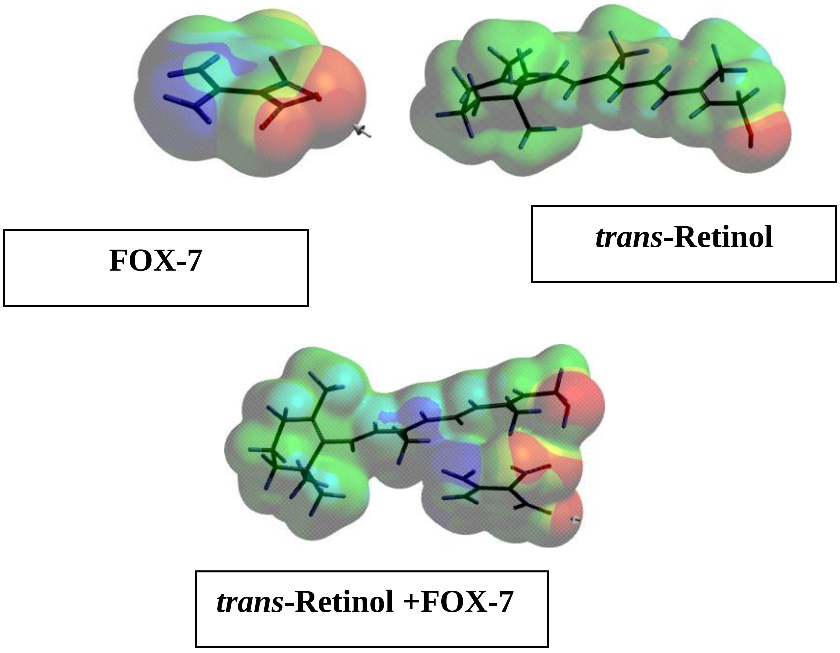


Figure 8. Optimized structure of *trans*-retinal +FOX-7 system.

Figure 9 shows the electrostatic potential maps of the systems considered where the blue-bluish and red-reddish regions stand for positive and negative potential regions, respectively.



FOX-7

trans-Retinol

trans-Retinol +FOX-7

Figure 9. Electrostatic potential maps of the structures considered.

As seen in the figure, while the composite forms the retinol moiety acquires more positive potential as compared to the original retinol component. Conversely, in the composite form the nitro groups of FOX-7 moiety becomes less negative potential region compared to its free component case.

4. Conclusion

The present DFT treatment on the possible interaction of trans-retinol and FOX-7 has revealed that these molecules undergo an interaction more intricate than some simple interactions of dipoles, charges and/or dipole and charges. The calculated IR and UV-VIS spectra indicate also some molecular orbital interactions prevailing between these molecules. The present study may shed some light on the influential effect of FOX-7 on the retinol-retinal metabolism of vision process. The present treatise involves calculations in vacuum conditions. However, a further study in aqueous medium will be beneficial to understand hazardous effect of FOX-7 in human body.

References

1. C. Berdanier, *Advanced Nutrition Micronutrients*. Boca Raton, Fla: CRC Press., 1997.

2. D.A.Bender, *Nutritional Biochemistry of the Vitamins*, Cambridge University Press, Cambridge 1995.

3. G. Wolf, 2001. *Discovery of vitamin A. Encyclopedia of Life Sciences*. Hoboken, NJ: John Wiley & Sons., 2008.

4. P. Politzer and J.S. Murray, *Energetic Materials*, Part 1. Amsterdam: Elsevier, 2003.

5. I.J. Lochert, *FOX-7 - A New Insensitive Explosive*, FOX-7. DSTO Aeronautical and Maritime Research Laboratory 506 Lorimer St, Fishermans Bend, Victoria 3207 Australia 2001, AR-012-065, November 2001.

6. N.V. Latypov, J. Bergman, A. Langlet, U. Wellmar, and U. Bemm, Synthesis and reactions 1,1-diamino-2,2-dinitroethylene, *Tetrahedron* 54 (1998), 11525-11536.

7. U. Bemm and H. Östmark, 1,1-Diamino-2,2-dinitroethylene: a novel energetic material with infinite layers in two dimensions, *Acta Crystallogr C* 54 (1998), 1997-1999.

8. N.V. Latypov, A. Langlet and U. Wellmar, *New chemical compound suitable for use as an explosive, intermediate and method for preparing the compound*, Patent WO99/03818; 1999.

9. H. Östmark, H. Bergman, U. Bemm, P. Goede, E. Holmgren, M. Johansson, A. Langlet, N.V. Latypov, A. Petterson, M.L. Petterson, N. Wingborg, C. Vörde, H. Stenmark, L. Karlsson and M. Hihkiö, *2,2-Dinitro-ethene-1,1-diamine (FOX-7) - properties, analysis and scale-up*, 32nd International Annual Conference of ICT on Energetic Materials- Ignition, Combustion and Detonation, Karlsruhe, Germany; 2001.

10. H. Östmark, A. Langlet, H. Bergman, N. Wingborg, U. Wellmar, and U. Bemm, *OX-7- A new explosive with low sensitivity and high performance*, The 11th International Detonation Symposium, Colorado, USA; 1998.

11. H Bergman, H. Ostmark, A. Pettersson, M.L. Petterson, U. Bemm, and M. Hihkio, *Some initial properties and thermal stability of FOX-7*, Insensitive Munitions and Energetic Materials Symposium (NDIA). Tampa, Florida, USA;1999.

12. W.A. Trzciński and A. Belaada, 1,1-Diamino-2,2-dinitroethene (DADNE, FOX-7) – properties and formulations (a Review), *Central European Journal of Energetic Materials* 13(2) (2016), 527-544.

13. B. Janzon, H. Bergman, C. Eldsater, C. Lamnevik, and H. Ostmark, FOX-7 – *A novel, high performance, low vulnerability high explosive for warhead applications*, 20th Int Symp Ballistics. Orlando, Florida,USA: September 23-27; 2002.

14. Y.N. Matyushin, G.T. Afanas'ev, V.P. Lebedev, M.N. Mahov and V.I. Pepekin, *TATB, and FOX-7: Thermo chemistry, performance, detonability, sensitivity*, 34th Int Annu Conf ICT, Karlsruhe, Germany: June 24-27; 2003.

15. A.J. Bellamy, N.V. Latypov and P.Goede, *Studies on the nitration of new potential precursors for FOX-7*, New Trends Res Energ Mater Proc Semin.7th, Pardubice, Czech Republic: April 20-22; 2004.

16. S. Cudziło, Z. Chyłek and R. Diduszko, *Crystallization and characterization of 1,1-diamino-2,2-dinitroethene* (*DADNE*), 36th Int Annu Conf ICT. Karlsruhe, Germany. June 28-July 1; 2005.

17. W.A. Trzciński, S. Cudziło, Z. Chyłek and Szymańczyk L. *Investigation of sensitivity and detonation properties of FOX-7*, 37th Int Annu Conf ICT. Karlsruhe, Germany: June 27-30; 2006.

18. M. Anniyappan, M.B. Talawar, G.M. Gore, S. Venugopalan and B.R. Ganghe, Synthesis, characterization and thermolysis of 1,1-diamino-2,2-dinitroethylene (fox-7) and its salts, *J. Hazard. Mater B* 137 (2006), 812-819.

19. W.A. Trzciński, S. Cudziło, Z. Chyłek, L. Szymańczyk, Detonation properties of 1,1- diamino-2,2-dinitroethene (DADNE), *J. Hazard. Mater* 157 (2008), 605-612.

20. V.S. Mishra, S.R. Vadali, R.K. Garg, V.S. Joshi, R.D. Wasnik and S. Asthana, Studies on fox-7 based melt cast high explosive formulations, *Cent Eur J Energ Mater* 10(4) (2013), 569-580.

21. Y. Zhang, Q. Sun, K. Xu, J. Song, and F. Zhao, Review on the reactivity of 1,1-diamino- 2,2-dinitroethylene (FOX-7), Propellants Explos Pyrotech 41 (2016), 35-52.

22. K. Baum, N.V. Nguyen, R. Gilardi, J.L. Flippen-Anderson and C. George, Nitration of 1,1-diamino-2,2-dinitroethylenes, Journal of Organic Chemistry 57 (1992), 3026- 3030.

23. J.J.P. Stewart, Optimization of parameters for semiempirical methods I. Method, J Comput Chem 10 (1989), 209-220.

24. J.J.P. Stewart, Optimization of parameters for semi empirical methods II. Application, J. Comput Chem 10 (1989), 221-264.

25. A.R. Leach, *Molecular Modeling*, Essex: Longman, 1997.

26. P. Fletcher, Practical Methods of Optimization, New York: Wiley, 1990.

27. W. Kohn and L. Sham, Self-Consistent equations including exchange and correlation effects, J Phys Rev 140 (1965), 1133-1138.

28. R.G. Parr, W. Yang, Density Functional Theory of Atoms and Molecules, London: Oxford University Press, 1989.

29. A.D. Becke, *Density*-Functional exchange-energy approximation with correct asymptotic behavior, *Phys Rev A* 38 (1988), 3098-3100.

30. S.H. Vosko and L. Vilk, M. Nusair, Accurate spin-dependent electron liquid correlation energies for local spin density calculations: A critical analysis, *Can J Phys*; 58 (1980), 1200-1211.

31. C. Lee, W. Yang, R.G. Parr, Development of the Colle-Salvetti correlation-energy, formula into a functional of the electron density, Phys Rev B 37 (1988), 785-789.

32. SPARTAN 06, Wavefunction Inc., Irvine, CA: USA, 2006.

33. I.Fleming, *Frontier Orbitals, and Organic Chemical Reactions*, NY: Wiley, 1976.