A Theoretical Study on Cycloaddition of 2-Ethynyl-2, 3-Dihydrofurane and Phenyl Azide

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ABSTRACT

A theoretical study of the kinetics and mechanism of second-order intermolecular Cycloaddition of 2-Ethynyl-2,3-Dihydrofurane and Phenyl Azide was performed using DFT method at B3LYP level of theory with 6-311++G(d,p) basis set at 298.15K. Equilibrium molecular geometries and harmonic vibrational frequencies of the reactants, transition state, and product were calculated. The kinetic and thermodynamic parameters of the reaction were investigated. These calculations indicated that the reaction proceeds through a synchronous concerted mechanism.

Keywords: DFT; kinetics; Activation energy; 1,3- Diolar Cycloaddition: 2-Ethynyl-2,3-Dihydrofurane; Phenyl Azide

INTRODUCTION

Dipolar Cycloaddition, DC, reaction is one of the most important methods for designing different kinds of heterocyclic compounds that have a significant usage in organic synthesis. A lot of organic compounds are products of DC reactions. They consist of compounds with different ring size and atoms. 1,3-DC is one type of dipolar cycloadditions that is used to synthesize of varies five-member ring hetrocycles. Usually in 1,3-DC reaction a carbon-carbon double bond reacts with a three member group of polar atoms [1]. In this concerted step two π bonds are broken and two *sigma* bonds are formed [2]. Azide are compounds that undergo 1, 3-DC reaction. As we know these compounds are important precursors for the synthesis of heterocyclic organic compounds. They are considered to be important for, biological applications [3]. Also azide derivatives are applied in rubber, polymers and dyes technology, as well as in pharmaceuticals, pesticides and herbicides developments [4,5].
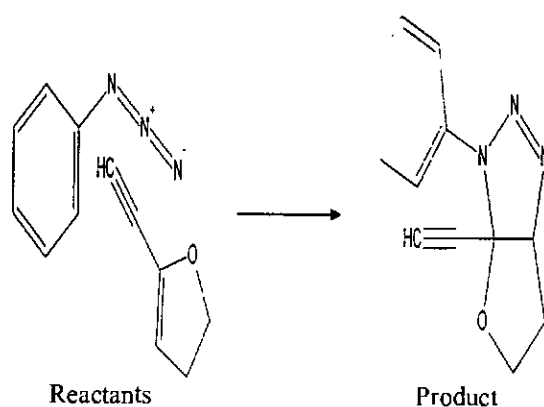
Scheme 1. Reaction of 2-Ethynyl-2,3-Dihydrofurane and Phenyl Azide.

Some authors studied effect of different solvents on these types of reactions experimentally [7,9]. This reaction usually shows inverse dependence of the rate constant on the polarization of the medium, the reaction being slowed in polar media [6-8], intermediate cases also known. The

Molecular Orbital Theory (MOT) has been used to explain some of the interesting aspects of different tips of these reactions. In this work, we investigated the mechanism, kinetic, and thermodynamic parameters on the reaction of 2-Ethynyl-2,3-Dihydrofurane and Phenyl Azide (see scheme 1).

COMPUTATIONAL DETAILS

The structures corresponding to the reactants, TS, and product were optimized and the electronic structures and harmonic vibrational frequencies of all stationary points along the reaction pathway were calculated using Gaussian 03 computational package [10] with DFT methods.

Optimization of the geometries of the stationary points on the potential energy surfaces were performed using Beck's there-parameter hybrid exchange functional with the correlation functional of Lee ,Yang, Parr (B3LYP) [11,12] using the 6-311++g(d,p) basis set [13]. The synchronous transit guided quasi Newton (STQN) method [14, 15] was used to locate the TS. The intrinsic reaction coordinate (IRC) method [16, 17] was also applied in order to check and obtain the profiles connecting the TS to the two associated minima of the proposed mechanism. The natural bond orbital (NBO) analysis [18, 19] was also applied to determine the charge changes occurring in the studied process. All minimum

and transition state structures are verified by vibrational frequency analysis.

The activation energies and Arrhenius factors were computed using eqns. (1) and (2), respectively, which were derived from the transition state theory [20, 21].

$$E_a = \Delta H^\# + 2RT \tag{1}$$

$$A = (ek_B T / h) \exp(\Delta S^\#(T) / R) \tag{2}$$

The degree of aromaticity of a polycyclic conjugated system was characterized by Bird's aromaticity indices [22, 23] and shielding constants of the magnetic field in the center of aromatic rings (NICS) [24]. Indices NICS were calculated by B3LYP/6-311++G(d, p).

RESULTS

Scheme (2) shows the optimized structures of reactants, TS, and product with the selected geometrical parameters at the B3LYP/6-311++G (d,p) shown in Table 1. The bond lengths of the transition state, TS, were calculated using the B3LYP level of the theory using 6-311++G (d,p) basis set. Throughout this paper, all inter nuclear distances and angles are in angstroms and degrees, respectively.

Reactants   Transition State   Product
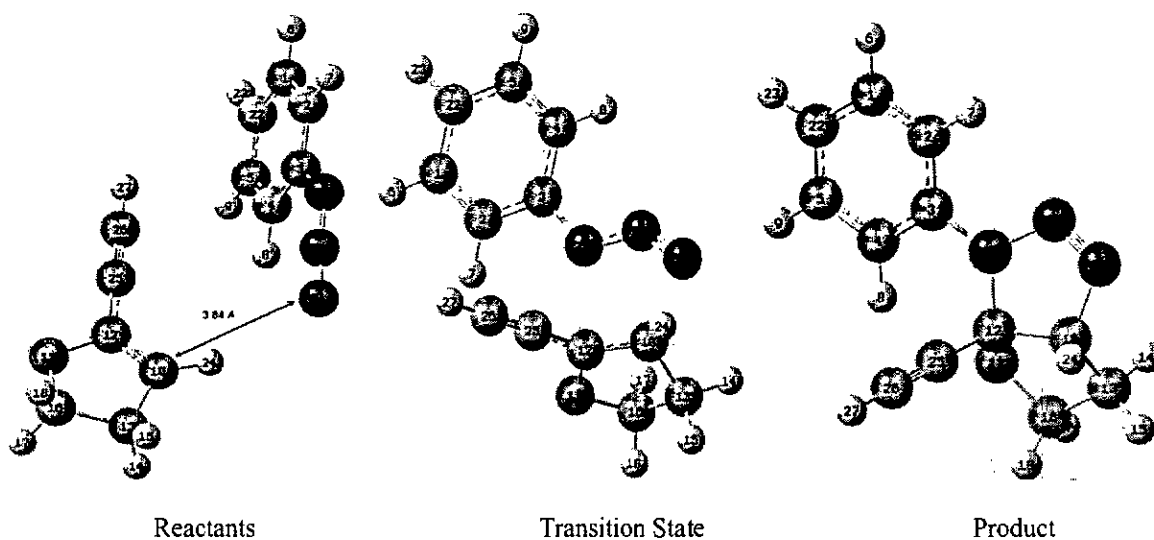
Scheme 2. Optimized geometries of reactants, TS, and product for the studied reaction at the B3LYP/6-311++G (d,p) level.

The Concerted mechanism is initiated with the N19-N20 and C10-C12 π bond cleavage and C10-N21 and C12-N19 bond formation. According to Table 1 the transition structure of the reaction has breaking C10-C12 and N19-N20 bonds distances of 1.40 and 1.27 angstrom respectively, and forming C12-N19 and C10-N21 bonds distances of 2.43 and 1.96 angstrom, respectively. The Pauling relation [25] was used to determine the related partial bond orders and values of 0.857, 0.794, 0.026, and 0.141 were obtained, respectively. The obtained partial bond orders indicate that 14.3% and 20.6% of π bond in N19-N20 and C10-C12 is broken respectively, whereas C10-N21 and C12-N19 have only 2.6% and 14.1% reaching to the transition state, respectively. The extent of broken and formed bonds in transition state shows that a synchronous concerted mechanism has occurred for the Cycloaddition of 2-Ethynyl-2,3-Dihydrofurane and Phenyl Azide. B3LYP/6-311++G (d,p) results for the reaction path are shown in Fig 1. It demonstrates the energy as a function of the reaction coordinate, C10-N21 and C12-N19, and represents the minimum energy path which connects the reactants to the product through the saddle point.
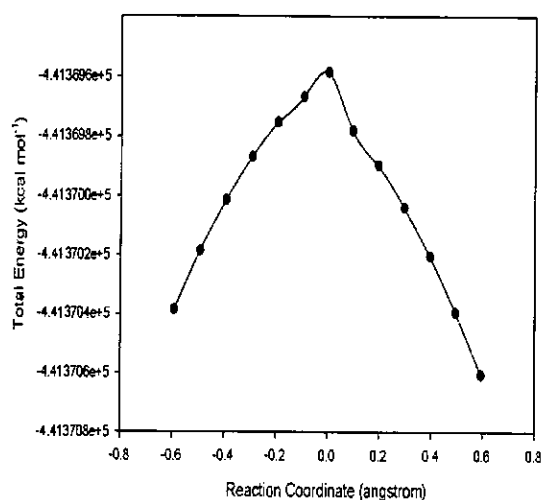
Table 1. Key geometrical parameters of the reactants, TS and product at the B3LYP/6-311++G (d,p) level of theory

Bond length	Reactant	TS	Product
C10-C12	1.34	1.40	1.56
N19-N20	1.23	1.27	1.37
N20-N21	1.13	1.19	1.25
C10-N21	–	2.43	1.48
C12-N19	–	1.96	1.45

Table 2 shows the charge distribution in the reactant, TS and the charge difference between TS and reactant (Δcharge) by means of NBO analysis. The results indicate that a small negative charge developed on N19, N20, and N21 at the TS, which demonstrates that N20-N19 bond cleavage is faster than C10-N21 bond formation. In addition, the charge difference shows that electron donor groups at N20 and N21 accelerate the reaction, whereas at C10 and C12 positions opposite results are observed.

Table 2. Distributed NBO charges on the reactants and TS at the B3LYP/6-311++G(d,p) level of theory (the numbering of atoms is like that in scheme 2)

	N19	N20	N21	C10	C12
Reactant	-0.3239	0.2422	-0.0569	-0.2476	0.2567
TS	-0.3331	0.1228	-0.1259	-0.2215	0.3108
ΔCharge	0.0092	0.1194	0.069	-0.0261	-0.0541

Table 3 presents NICS values for reactant, TS, and product at B3LYP/6-311++G(d,p) level of theory. The calculated NICS indices showed a decreasing in the degree of aromaticity when going from reactants to the transition structure and product.

Table 3. NICS values for reactant, TS, and product at B3LYP/6-311++G(d,p) level of theory

	Reactant	TS	Product
NICS(1)/ppm	9.6378	9.2655	8.8836

The imaginary frequency for the transition structure was calculated to confirm the TS B3LYP/6-311++G(d,p). Table 4 presents, $\Delta G^{\#}$, $\Delta H^{\#}$, $\Delta S^{\#}$, activation energy, Arrhenius pre-exponential factor and rate constant for the studied reaction at B3LYP/6-311++G(d,p) level of the theory. As can be seen in Table 4, the Gibbs free energy barrier for the TS formation in gas phase is 26.9 kcal mol⁻¹.

Fig. 1. Schematic energy profile of the potential energy surface for the studied reaction at B3LYP/6-311++G** level of theory.

Table 4. Thermodynamic and kinetic parameters of the reaction at B3LYP/6-311++G(d,p) level of the theory. Gibbs free energy, enthalpy, and activation energy are in kcal mol^{-1}, and entropy is in cal mol^{-1} K^{-1}

	$G^{o,\#}\Delta$	$k(M^{-1}S^{-1})$	$H^{o,\#}\Delta$	E_a	logA	$S^{o,\#}\Delta$
Gas phase	26.9	1.2×10^{-7}	20.1	20.7	8.2	-22.8

CONCLUSTION

Cycloaddition of 2-Ethynyl-2,3-Dihydrofurane and Phenyl Azide was studied by the Density Functional theory at B3LYP/6-311++G (d,p) level of the theory. The calculated Gibbs free energy in gas phase is about 26.9 kcal mol^{-1} at 298.15 K. The calculated Gibbs free energy of activation shows the reaction can be done at room temperature, but its rate is slow. The reason can be due to the increasing of stability of the structures because of elevation of aromaticity, from reactant to product.

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