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The Photochemical Dimerization of 4-Nitro-2-Phenylindone. A DFT Study

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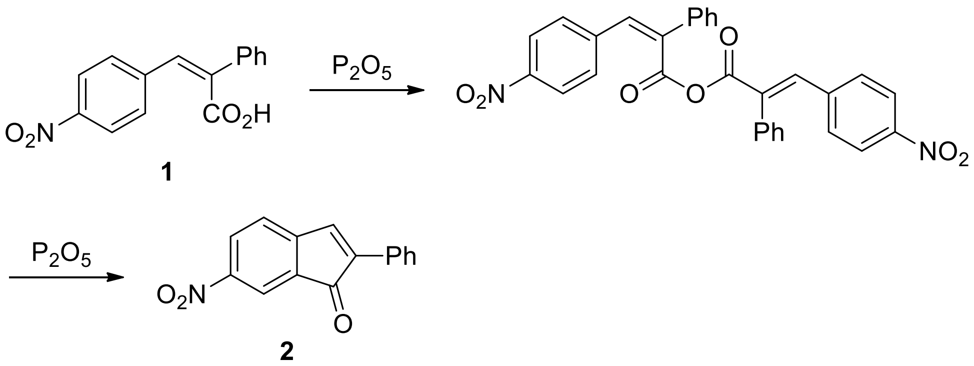
Abstract

A DFT study of the photochemical dimerization on 4-nitro-2-phenylindone has been performed. The reaction was performed by Marussia Bakunin in 1911 but the reaction products were not identified. Calculations allow us to know that the reaction occurred through the first excited singlet state. The nature of the first excited singlet state allowed the formation of both head-to-head and head-to-tail dimers. Finally, the main product was the *syn-trans* head-to-tail dimer, while the other two compounds found by Bakunin in lower yields were the *syn-trans* head-to-head dimer and the *syn-cis* head-to-tail dimer. The results described by Bakunin can not be interpreted assuming the reaction occurred through the formation of the excited triplet state.

1. Introduction

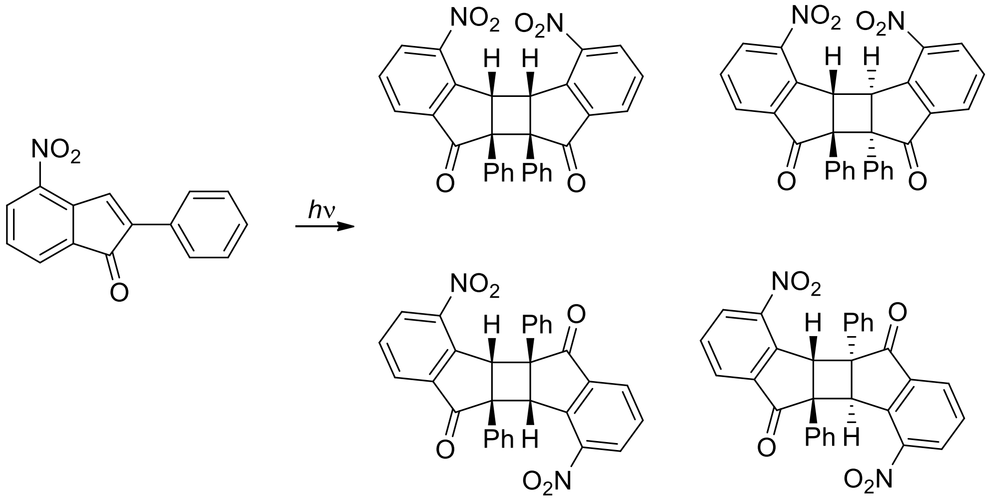
A researcher who needs to make a career in the academic field must consider, when choosing the field of his research, whether a research topic is sufficiently fashionable to be accepted in journals with a high impact factor and above all to be able to guarantee his articles a good number of citations. Unfortunately, this is the world we live in, and the tools we have given ourselves to evaluate scientific research induce behaviors of this type. This way of working leads to the neglect of research areas considered niche. We no longer have this type of problem, as I no longer have career ambitions. I can therefore devote myself to things that other researchers younger than me would neglect. I therefore want to propose in this article an attempt to provide a solution to a small problem that has remained unsolved for many years. In other words, I will propose the discussion of a cold case, to use detective terminology. For this reason, it is good to start by introducing the actors of this unsolved case.

The main actor was Marussia Bakunin, daughter of Michail Bakunin, the main exponent of anarchic movement in the XIX century. Michail Bakunin, during his exile in Siberia, at 44 years old, married the eighteen-year-old Antonia Kwiatkowska. Bakunin wrote in a letter that he married Antonina because he wanted to remove her from the backward environment of Siberia. Between 1865 and 1867 Antossia was in Naples where she met Carlo Gambuzzi, a socialist doctor, and a romantic relationship, kown to Michail Bakunin, was born between the two. From this relationship three children (Carlo, Sofia, and Maria) were born, children all recognized by Bakunin. In 1876 Michail Bakunin died and Antossia married Carlo Gambuzzi, moving to Naples, where Maria (Marussia) grew. In 1890 she enrolled in the chemistry degree course at the University of Naples, where she graduated in 1895. In 1911 she became professor of organic chemistry, role which she held until 1948 **[1]**. During this period, working on the products deriving from the Perkin reaction, she described a synthesis of 2-phenylindones **2** from the corresponding cinnamic acid derivatives **1** (Scheme 1) **[2]**.



Scheme 1

Studying the chemical reactivity of **2**, she found that the irradiation with solar light in solution of this substrate allowed the formation of the corresponding dimers **[3]**. She found three dimers (four dimers could be obtained) and one of these dimers was double the quantity compared to the other two (Scheme 2). Marussia Bakunin cannot identify the products.



Scheme 2

The aim of this work is to give a possible indication on the nature of the products of this reaction. The correct identification of the products can allow us to understand the mechanism of the dimerization of cinnamic acid derivatives in solution. In fact, the photochemical dimerization of cinnamic acid is a well-known reaction studied from the beginning of XX century **[4]**. However, most of the reactions had been performed in the solid phase, while very few data are available for reactions in solution. In solution, cinnamic acid derivatives can allow an efficient photochemical *cis-trans* isomerization that inhibited the dimerization reaction. However, the dimerization in solution can have significant biological implications. In fact, cinnamic acid dimers have been found in alkaloids identified in (Figure 1) **[5]**. In these molecules the acid is esterificated by ecgonine. Both compounds found have a powerful cardiotoxic action and their presence in cocaine can make it even more dangerous.

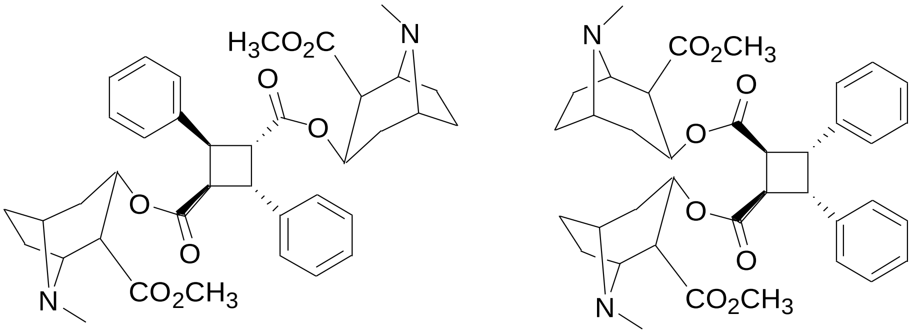


Figure 1. Dimers of cinnamic esters in *Erythroxylum coca* and *Erythroxylum novogranatense.*

Some years ago, we found that heterocyclic substituted cinnamic acid derivatives can allow the photochemical dimerization if the reaction was sensitized by benzophenone **[6-14]**. In this case the obtained reaction products can be explained considering the relative stability of the biradical intermediates generated by the coupling of the starting material in its excited triplet state and another molecule of the monomer. One of the targets of this work is the verification of the possibility of using this approach also on non-sensitized reactions.

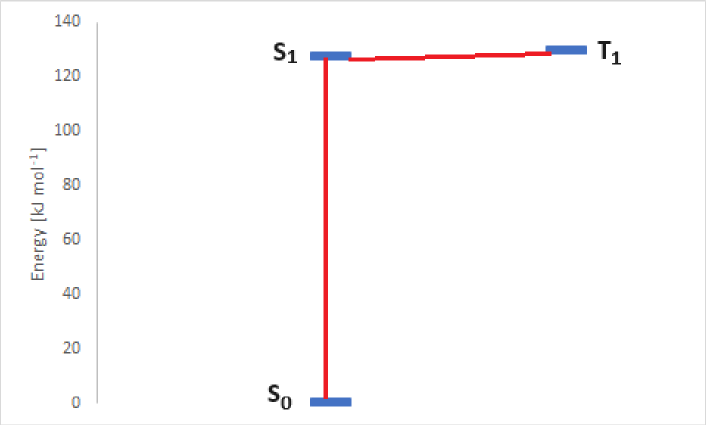


Figure 2. Excited singlet state and triplet state of 4-nitro-2-phenylindone.

2. Results and Discussion

We performed some DFT calculations (B3LYP/6-311G+(d,p) on Gaussian 09 **[15]**) on the reaction described in the Scheme 2. 4-Nitro-2-phenylindone showed an absorption at 938 nm, corresponding to a π,π* excited singlet state at 127.56 kJ mol^{-1}. The triplet state was found at 129.27 kJ mol^{-1} (Fig. 2). The triplet state showed an energy higher than the excited singlet state, even if only slightly. In this condition, the intersystem crossing could be inefficient, and the triplet state could be unpopulated, or populated with a very low quantum yield.

On the basis of the above reported data, the dimerization reaction of 4-nitro-2-phenylindone could occur through the first excited singlet state.

The orbitals involved in the reaction are reported in Figs. 3 and 4. The best interaction between the molecular orbitals is that between the LUMO of S_0 and the HSOMO of the singlet excited state. Considering the frontier orbitals rule, the reaction is allowed. The superposition of the atomic coefficients on the double bond on the HSOMO of the excited singlet state and the atomic coefficients on the double bond on the LUMO of the ground state allowed [2+2]-cycloaddition.

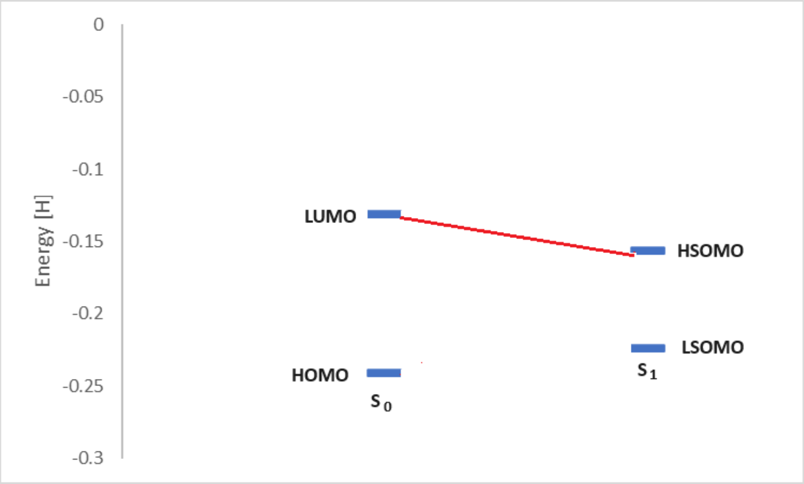


Figure 3. Frontier orbitals in the reaction of 4-nitro-2-phenylindone through the first excited singlet state.

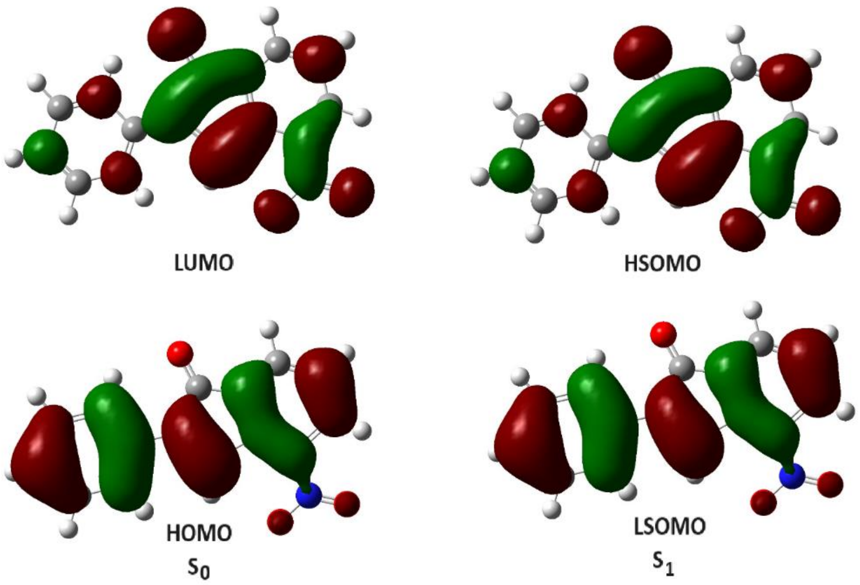


Figure 4. Molecular orbitals involved in the photochemical dimerization of 4-nitro-2-phenylindone.

Furthermore, it is accepted that photochemical [2+2]-cycloaddition reactions occur in [2s + 2s] suprafacial manner **[16]**. Considering that the atomic coefficients on the HSOMO of the first excited state and LUMO of the ground state, 0.10 and -0.10 were obtained for the carbon atoms of the double bond. In this case, both had-to-head and head-to-tail approaches were allowed. The main product was the *syn-trans* head-to-tail dimer, while the other two compounds found by Bakunin in lower yields were the *syn-trans* head-to-head dimer and the *syn-cis* head-to-tail dimer.

The singlet state can interconvert into the dimers without any apparent transition state. The results are reported in the Figure 5.

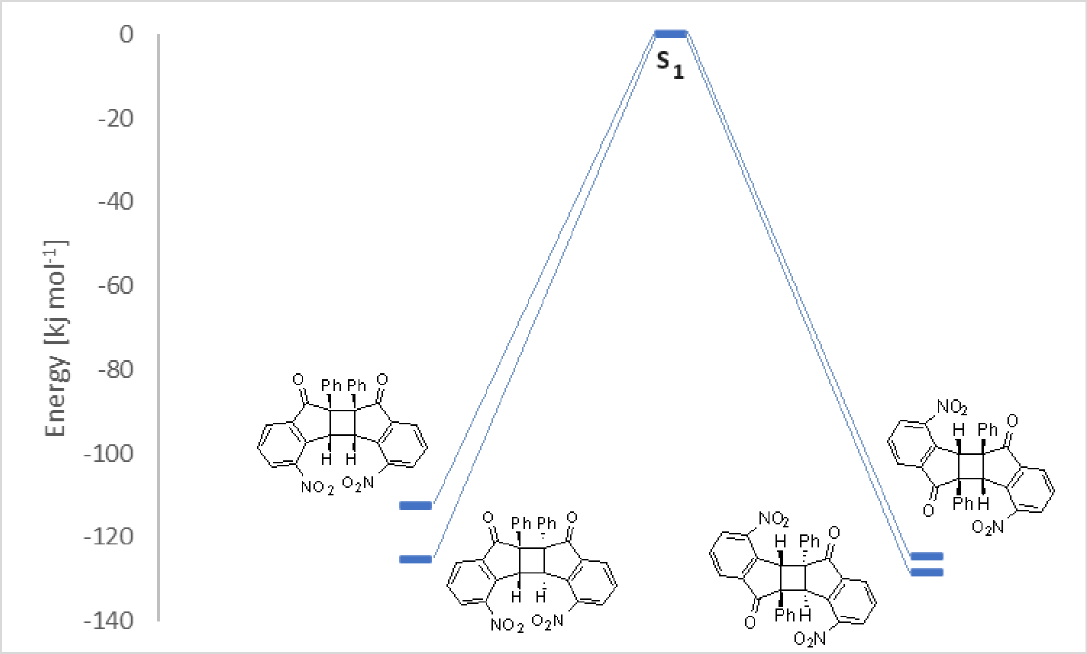


Figure 5. Formation of dimers of 4-nitro-2-phenylindone considering a reaction through a singlet excited state.

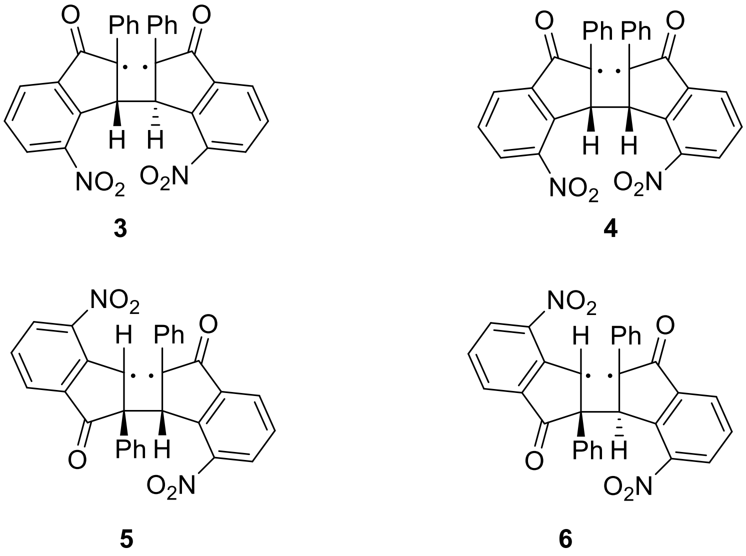


Figure 6. Possible biradical intermediates in the dimerization of 4-nitro-2-phenylindone *via* triplet state.

On the basis of our hypothesis, the dimerization reaction of 4-nitro-2-phenylindone allowed the formation, as main product, of the *syn-trans* head-to-tail dimer, while the other two compounds found by Bakunin in lower yields were the *syn-trans* head-to-head dimer and the *syn-cis* head-to-tail dimer. However, considering that the very little difference in the energy between the excited singlet state and the triplet state, we also verified the possible formation of the dimers through the formation of the triplet state. In this case, the reaction had to occur through the formation of the biradical intermediates reported in the Fig. 6.

The chemical behavior of these biradical intermediates is reported in Fig. 7. As a first result it is possible to note that the head-to-tail biradicals showed an energy higher than that of the triplet state, Then, they cannot be formed during the reaction. Only head-to-head biradicals can be obtained. Furthermore, *cis* biradical intermediate is more stable than the *trans* biradical. They can evolve, also in this case, without an apparent transition state, as reported in the dimerization of cinnamic ester **[14]**.

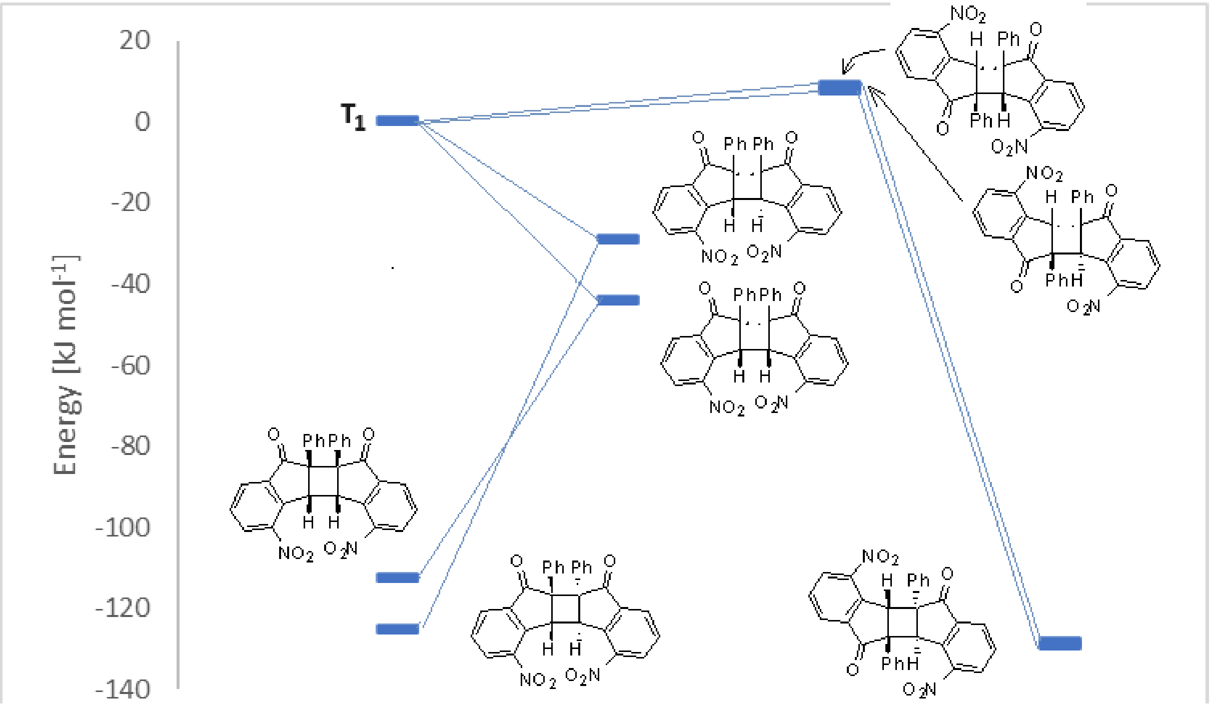


Figure 7. Formation of biradical intermediates and dimers in the reaction of 4-nitro-2-phenylindone *via* the triplet state.

3. Conclusion

In conclusion, if the photochemical dimerization reaction of 4-nitro-2-phenylindone occurred through the triplet state, only two products could be obtained. This result is not in agreement with the original observations of Bakunin, that claimed the formation of three dimers **[3]**. The above reported results are in agreement, on the contrary, with the hypothesis that the reaction occurred *via* the first excited singlet state.

4. Declarations

4.1 Conflict of interest

The Authors declare that there is no conflict of interest.

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