Re-examination of the Anodic Oxidation of \textit{N,}\textit{N}-Dimethylaniline, Using Parametric Method 3

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A semi-empirical calculation (PM3) was applied to elucidate the anodic oxidation mechanism of \textit{N,}\textit{N}-dimethylaniline (DMA) and the dimerization of a cation radical (A) derived from DMA was ruled out. The heat of reaction value of the dimerization of A was 42.43 kcal/mol. We propose the following. Cation radical A reacts with DMA to generate another cation radical (D). This reaction was exothermic and the heat of reaction value and the activation energy were $-0.35$ kcal/mol and 1.31 kcal/mol, respectively. Deprotonation of D by DMA gives neutral radical (E), which is oxidized to TMB by A. All these reactions were exothermic.

**Key words** PM3; \textit{N,}\textit{N}-dimethylaniline; oxidation; MO; radical

Much attention has been devoted to the anodic oxidation of \textit{N,}\textit{N}-dimethylaniline (DMA) and the electrolysis has been carried out in various conditions.\textsuperscript{3} All the investigators, with the exception of Hand and Nelson, found \textit{N,}\textit{N},\textit{N}',\textit{N}''-tetramethylbenzidine (TMB) to be the predominant product.\textsuperscript{5} It was reported that the primary electrode reaction was a one-electron transfer to form a cation radical (A) which, then, coupled to form TMB. A semi-empirical calculation (parametric method 3 (PM3)) was applied to elucidate the mechanism in more detail.

PM3 is the latest Hamiltonian contained in the MOPAC program and has been reviewed by Stewart.\textsuperscript{3} Friant-Michel \textit{et al.} also used PM3 effectively to elucidate the cyclization mechanism of \textit{a}- and \textit{b}-d-glucosyl azides.\textsuperscript{4}

**Results and Discussion**

The presence of A in the primary anodic oxidation of DMA was suggested by cyclic voltammetry.\textsuperscript{5-7} Dimerization of A, that is reaction 1) shown in Chart 1, is an established theory as the generation mechanism of TMB.

We performed the calculation based on the assumption that DMA was a proton acceptor. The total energy of reactants and products of reaction 1) were estimated using PM3, and the results are shown in Table 1.

The molecular orbital (MO) calculation was performed using HyperChem release 5.1. Before single point calculation, geometry optimization was initially performed using MM+, then with UHF (spin unrestricted Hartree–Fock) calculation using the Polak–Ribiere algorithm as the minimization algorithm until the total root-mean-square (RMS) gradient was reduced to 0.01 kcal/(\textit{A} mol).

As shown in Table 1, the total energy of reactants and products were $-117665.85$ kcal/mol and $-117706.10$ kcal/mol respectively, so the heat of reaction value ($\Delta E = E_{\text{react}}$ (sum of total energies of reactants) $- E_{\text{prod}}$ (sum of total energies of products)) was $-40.25$ kcal/mol. This fact suggests that the overall reaction is exothermic and reasonable. However, the reaction is a multi-step one. The coupling of A shown in Chart 2 was examined initially.

The total energy of the dication (B) was estimated at $-58624.95$ kcal/mol, which was more than double that of A ($2\times(-29333.69$ kcal/mol) $= -58667.38$ kcal/mol) by 42.43 kcal/mol. Therefore, the reaction 2) does not proceed at room temperature.

As another mechanism, deprotonation of A prior to coupling was postulated and is shown in Chart 3. The total energy of reactants and products of reaction 3) except C are shown in Table 1 and that of C was estimated at $-29103.69$ kcal/mol. Therefore, the sum of total energy of products was

![Chart 1](NII-Electronic Library Service)

![Chart 2](NII-Electronic Library Service)

![Chart 3](NII-Electronic Library Service)

**Table 1. Total Energy of Reactants and Products in the Reaction 1)**

<table>
<thead>
<tr>
<th>Reactant</th>
<th>Total energy (kcal/mol)</th>
<th>Product</th>
<th>Total energy (kcal/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>\textit{N,}\textit{N}-Dimethylaniline (A)</td>
<td>$-29333.69$</td>
<td>\textit{N,}\textit{N},\textit{N}',\textit{N}''-Tetramethylbenzidine (TMB)</td>
<td>$-58302.10$</td>
</tr>
<tr>
<td>\textit{N,}\textit{N}-Dimethylaniline (DMA)</td>
<td>$-29500.11$</td>
<td>Protonated DMA</td>
<td>$-29702.00$</td>
</tr>
</tbody>
</table>

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Table 2. Sum of Total Energy of Reactants and Products in the Reactions in Chart 4

<table>
<thead>
<tr>
<th>Reaction No.</th>
<th>Reactants ($E_{\text{react}}$)</th>
<th>Products ($E_{\text{prod}}$)</th>
<th>$\Delta E$ ($E_{\text{react}} - E_{\text{prod}}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5)</td>
<td>$-58833.80$ kcal/mol</td>
<td>$-58834.15$ kcal/mol</td>
<td>$-0.35$ kcal/mol</td>
</tr>
<tr>
<td>6)</td>
<td>$-88334.26$ kcal/mol</td>
<td>$-88343.32$ kcal/mol</td>
<td>$-9.06$ kcal/mol</td>
</tr>
<tr>
<td>7) Path A</td>
<td>$-87975.01$ kcal/mol</td>
<td>$-87989.44$ kcal/mol</td>
<td>$-14.43$ kcal/mol</td>
</tr>
<tr>
<td>7) Path B</td>
<td>$-87975.01$ kcal/mol</td>
<td>$-88004.10$ kcal/mol</td>
<td>$-29.09$ kcal/mol</td>
</tr>
</tbody>
</table>

$-58805.69$ kcal/mol and that of reactants was $-58832.94$ kcal/mol. The heat of reaction value was $27.25$ kcal/mol. Reaction 3) also does not proceed at room temperature.

As an alternative mechanism, an electrophilic addition of $A$ to DMA and following reactions were postulated and are shown in Chart 4. The total energy of cation radical (D), which was a product of reaction 4), was $-58834.15$ kcal/mol and below $-58833.80$ kcal/mol, which was the sum of the total energy of reactants, that is $A$ and DMA. The total energy of the transition state shown in Fig. 1 was $-58832.49$ kcal/mol, so the activation energy ($E_{\text{act}} - E_{\text{trans}}$ (sum of total energies of transition state) $E_{\text{react}}$) was only $1.31$ kcal/mol. The synchronous transit method of transition state searching was applied, then the eigenvector following was used with a RMS gradient termination criterion of $0.01$ kcal/Å/mol. DMA was abundant in the electrolyte, so the reaction 5) seems very fast. The high reactivity of reaction 5) well explains the fact that $A$ was not detected with electron spin resonance spectrometry.5,7)

DMA abound in the solution abstracted a proton from D to generate a neutral radical (E). Because E has one more electron than TMB, E must be oxidized to generate TMB. Using the rotating ring-disk electrode technique, Galus et al. reported that only DMA and TMB were oxidized on the anode.6) Their results suggests that the oxidant in this step was not the electrode but A.

Two types of reactions with A were predicted: one-electron oxidation following deprotonation (Path A) and hydrogen abstraction (Path B). These reactions were exothermic as shown in Table 2. It is difficult to judge which path is followed because we failed to obtain a transition state for either one. In either case, two molecules of A were consumed to generate TMB and two molecules of DMA were protonated in the schemes shown in Chart 4. The schemes are in agreement with reaction 1) stoichiometrically.

Experimental
Apparatus Semi-empirical calculation was carried out as described previously.6)

References and Notes