Catalysis of Oxidation of Nitrogen Compounds by Flavin Coenzymes in the Presence of Light*

WILHELM R. FAISELL, CHOONG W. CHUNG,† AND COSMO G. MACKENZIE

From the Department of Biochemistry, The University of Colorado School of Medicine, Denver, Colorado

(Received for publication, November 3, 1958)

When it was discovered in this laboratory that sarcosine and dimethylglycine are oxidized to formaldehyde by riboflavin phosphate and riboflavin in the absence of protein, this observation was pursued, not only because of our interest in the enzymatic oxidation of these substrates, but also because of its implications regarding the origin of biochemical reactions. Subsequent studies to be described below, have demonstrated that these nonenzymatic reactions are photochemical and occur only when the nitrogen compounds, plus catalytic amounts of the riboflavin phosphate are exposed to light. The mechanism of this photooxidation has been investigated by employing as substrates sarcosine and dimethylglycine labeled with C14 and also homologous derivatives of these amino acids.

RESULTS

We chose first to examine the oxidation of sarcosine in the presence of riboflavin phosphate, and for this purpose employed both the carboxyl- and the methyl-labeled amino acid. The results of these experiments are presented in Table I.

It will be seen that the products in the photooxidation of sarcosine with riboflavin phosphate are carbon dioxide, methylamine, and formaldehyde. Thus, the C14-carboxyl group is cleaved to give high yields of radiocarbon dioxide and the labeled methylamino group is recovered as radiomethylamine. On the other hand, the large amounts of formaldehyde produced from either carboxyl- or methyl-C14-sarcosine are not significantly labeled. Thus, when the reaction described in Table I was stopped for analysis, approximately 10 μmoles of formaldehyde had accumulated. However, of this quantity only 0.2 μmole was radioactive in the case of the C14H3-sarcosine and only 0.007 μmole of radiomethylamine was obtained from the C14OOH-sarcosine. In other words, neither the N-methyl nor the carboxyl carbon had contributed significantly to the formaldehyde which accumulated during the reaction and it could be concluded therefore that the formaldehyde was derived almost exclusively from the α-carbon.

When the solutions from the experiments with the sarcosine-C14H3 were chromatographed on paper with n-butanol-acetic acid-water (4:1:5) only three radioactive spots were detectable: unreacted sarcosine (Rf, 0.15), methylamine (Rf, 0.29), and a ninhydrin-negative region with an Rf of 0.62. The latter has not yet been identified. Furthermore, no glycine could be detected, providing additional evidence that N-demethylation is insignificant in the photooxidation of sarcosine.

We were unable to detect the intermediate formation of a keto acid such as glyoxylic acid from sarcosine in these experiments. Thus, no C14-glyoxylic acid could be isolated in the reaction employing the carboxyl-C14-sarcosine (Table I). Moreover, when 20-μmole levels of glyoxylic acid, both in the absence and presence of 20 μmoles of methylamine, were subjected to riboflavin phosphate and light under the same conditions, no formaldehyde could be isolated.

Photooxidation of α-C14-dimethylglycine—In further isotope experiments, summarized in Table II, it was found that dimethylglycine is also oxidized photochemically with riboflavin phosphate and that the pattern of its oxidation is analogous to that of sarcosine. When the reaction was stopped for analysis, formaldehyde and dimethylamine had accumulated in almost equimolar quantities. By photometric analysis, a total of 12.6 μmoles of formaldehyde was found in the reaction mixture, and of this amount, 10.8 μmoles were radioactive. In other words, at least 85 per cent of the total formaldehyde which accumulated during the photooxidation of dimethylglycine was formed from the α-carbon. The remaining 15 per cent of the formaldehyde, representing only about 2 μmole, was derived from the dimethylamine in the reaction mixture, as will be shown in Table III, this secondary amine is also photooxidized with riboflavin phosphate to formaldehyde, but at only one-third the rate of dimethylglycine.

Finally, it will be noted in Table II that the α-carbon of the dimethylglycine suffered only a marginal oxidation (about 0.2 per cent) to the level of carbon dioxide and that neither sarcosine nor glycine could be detected chromatographically in the reaction mixture.

Production of Riboflavin Phosphate-2H and Hydrogen Peroxide in Photooxidation of Sarcosine—The data of Tables I and II demonstrate that sarcosine and dimethylglycine are oxidized photochemically by similar pathways. Aside from the production of amine, formaldehyde, and carbon dioxide from these two amino acids, the most obvious sign of chemical reaction is the uptake of oxygen, and it will be seen from the data of Tables I and II that about 1 mole of oxygen is consumed for every mole of formaldehyde which accumulates in the reaction mixture. At the same time, however, it can be demonstrated in such experiments that the flavin is serving as an electron carrier and that the oxygen taken up during the oxidation of the amino acids is due to the reoxidation of the reduced flavin. When, for exam-

* Supported by Grant No. A-969 C-5, National Institutes of Health, United States Public Health Service. An abstract of this paper has been published in Federation Proceedings, 17, 224 (1958).
† Present address, Department of Chemistry, University of Indiana, Bloomington, Indiana.
ple, the oxygen is excluded from the system, the reaction mixture soon becomes colorless; and, when oxygen is again admitted, the characteristic yellow color of the riboflavin phosphate reappears. Further analyses demonstrated that this oxidation of the reduced flavin with oxygen produces hydrogen peroxide and that for each mole of oxygen consumed, 1 mole of hydrogen peroxide accumulates.

The stoichiometry of the major reaction in the photooxidation of these N-methyl amino acids with riboflavin phosphate, under the conditions of our experiments, can therefore be summarized by the following equations for sarcosine:

\[
\text{Riboflavin} + \text{H}_2\text{C}-\text{NH}-\text{CH}_2-\text{COOH} + \text{H}_2\text{O} \rightarrow \\
\text{riboflavin-P-2H} + \text{H}_2\text{C}-\text{NH}_2 + \text{CH}_2\text{O} + \text{CO}_2
\]

\[
\text{Riboflavin-P-2H} + \text{O}_2 \rightarrow \text{Riboflavin-P + H}_2\text{O}
\]

**Table I**

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Oxygen uptake</th>
<th>Formaldehyde</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sarcosine-C(^{14})OH</td>
<td>12.8</td>
<td>0</td>
</tr>
<tr>
<td>Sarcosine-(\text{C}^{14})H(_2)</td>
<td>0.024</td>
<td>0.007</td>
</tr>
</tbody>
</table>

* Total formaldehyde.

**Table II**

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Oxygen uptake</th>
<th>Formaldehyde</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sarcosine-(\text{C}^{14})OH</td>
<td>12.8</td>
<td>0</td>
</tr>
<tr>
<td>Sarcosine-(\text{C}^{14})H(_2)</td>
<td>0.024</td>
<td>0.007</td>
</tr>
</tbody>
</table>

* Total formaldehyde.

**Table III**

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Oxygen uptake</th>
<th>Formaldehyde</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sarcosine-(\text{C}^{14})OH</td>
<td>12.8</td>
<td>0</td>
</tr>
<tr>
<td>Sarcosine-(\text{C}^{14})H(_2)</td>
<td>0.024</td>
<td>0.007</td>
</tr>
</tbody>
</table>

* Total formaldehyde.

The same order of reactivity holds for the methylaminoethanols and also the methylamines; i.e. the tertiary and secondary derivatives are several times more active than the primary compounds and, in analogy to betaine, the quaternary choline is not attacked. With both the glycine and amine series, approximately 1 mole of \(\text{O}_2\) is consumed for each mole of formaldehyde which accumulates. In the aminoethanol series, on the other hand, the oxygen uptake exceeds the quantity of formaldehyde found in the reaction mixtures, indicating that the alcohol carbons are also undergoing oxidation.

These results established, therefore, that with the simple amino compounds, susceptibility to photooxidation decreases in the order of tertiary > secondary > primary > quaternary, a sequence which also represents decreasing electronegativity of their amino groups. Furthermore, it will be seen that \(N\)-ethylglycine is less reactive than sarcosine and that glycyglycine has no activity in the system. Taken together, these findings suggested that the photooxidation of an amino compound with riboflavin phosphate is enhanced by the electronegativity of some site in the molecule, presumably because of the greater availability of electrons at the nitrogen atom.

The most direct evidence for this hypothesis was obtained when the dimethylglycine and sarcosine-riboflavin phosphate systems were subjected to various acidities. The results of these experiments are presented in Table III.

It will be seen in the N-methylglycine series that the quaternary derivative, betaine, is resistant to oxidation under these conditions and that of the other three acids, dimethylglycine and sarcosine are more readily oxidized than the primary glycine. The same order of reactivity holds for the methylaminoethanols and also the methylamines; i.e. the tertiary and secondary derivatives are several times more active than the primary compounds and, in analogy to betaine, the quaternary choline is not attacked. With both the glycine and amine series, approximately 1 mole of \(\text{O}_2\) is consumed for each mole of formaldehyde which accumulates. In the aminoethanol series, on the other hand, the oxygen uptake exceeds the quantity of formaldehyde found in the reaction mixtures, indicating that the alcohol carbons are also undergoing oxidation.

These results established, therefore, that with the simple amino compounds, susceptibility to photooxidation decreases in the order of tertiary > secondary > primary > quaternary, a sequence which also represents decreasing electronegativity of their amino groups. Furthermore, it will be seen that \(N\)-ethylglycine is less reactive than sarcosine and that glycyglycine has no activity in the system. Taken together, these findings suggested that the photooxidation of an amino compound with riboflavin phosphate is enhanced by the electronegativity of some site in the molecule, presumably because of the greater availability of electrons at the nitrogen atom.

The most direct evidence for this hypothesis was obtained when the dimethylglycine and sarcosine-riboflavin phosphate systems were subjected to various acidities. The results of these experiments are presented in Table III.

It will be seen in the N-methylglycine series that the quaternary derivative, betaine, is resistant to oxidation under these conditions and that of the other three acids, dimethylglycine and sarcosine are more readily oxidized than the primary glycine.
experiments, shown in Fig. 1, demonstrated that these amino acids are not oxidized when their amino nitrogens are in the quaternary form. Instead, the initial rate of photooxidation of dimethylglycine or sarcosine becomes significant only above pH 7.8, the pH range where the nitrogen loses its proton and thereby re-exposes the unshared electron pair. The degree of ionization of riboflavin phosphate itself does not change significantly in the pH range employed in these experiments.

In addition to the methylated glycines, aminoethanols, and amines, there are listed in Table III a number of other compounds which are oxidized with riboflavin phosphate under the conditions of our experiments. Among these substrates, \( \alpha \)- or \( \beta \)-alanine was found to be oxidized at approximately the same rate as glycine, while \( \alpha \)-L,N-methylalanine exhibited about 6 times the activity of alanine. Ammonia (or methylamine, in the case of the methylalanine) and acetaldehyde are products of these reactions. These results provide evidence, therefore, that the \( \alpha \)-amino acids are oxidized in a manner similar to the oxidation of the glycines and emphasize again that secondary amino compounds are more reactive than the primary compounds. \( \beta \)-Alanine is not oxidized under these conditions.

It will be seen that Versene (ethylenediaminetetraacetate) is particularly susceptible to photooxidation with riboflavin phosphate and also that formaldehyde is a product of its breakdown. Although Merkel and Nickerson (1) implicated Versene in a "photoreduction" of riboflavin phosphate, and Oster and Wotherspoon (2) have shown that Versene can be photooxidized with methylene blue, the results presented here are the first to show evidence that this commonly employed chelating agent gives rise to formaldehyde during the course of its oxidation.

In the case of methionine, whose rate of oxygen uptake in the riboflavin phosphate system is more than twice that for the glycine and alanine derivatives, neither \( \text{C}^4\text{H}_2\text{O} \) nor \( \text{C}^4\text{O}_3 \) was found to be a reaction product of the \( \text{C}^4\text{H}_2\text{N} \)-amino acid. \( \text{N} \)-methyl compounds such as adrenaline and nicotine are very reactive under the conditions of our experiments but just as in the case in the methionine they also fail to give rise to formaldehyde.

Fatty acid anions such as acetate, propionate, butyrate, valerate, and trimethylacetate are not oxidized in the riboflavin phosphate system.

Catalytic Function of Flavin System in Photooxidation—In the reactions described thus far, catalytic quantities of riboflavin phosphate will elicit photooxidation of the various nitrogen substrates. In order to determine whether the photodynamic efficiency of the flavin might be influenced by variations in its structure, riboflavin and FAD were compared with riboflavin phosphate for photo-activity against sarcosine and dimethylglycine.

The results of these experiments (Table IV) demonstrated that riboflavin and riboflavin phosphate, which differ only by a phosphate ester linkage, possess almost the same catalytic activity as measured by either the rates of oxygen uptake or formaldehyde production. FAD, on the other hand, is only 10 to 20 per cent as potent a catalyst as the other two flavins. In other words, the attachment of the adenylic acid moiety to the riboflavin phosphate molecule deters its photodynamic activity toward these amino acids.

This indication that the adenylic acid portion of FAD exerts an intramolecular "quenching" effect on the photodynamic activity of the riboflavin nucleus led to a study of free adenine and its nucleotides. As shown in Table V, the addition of adenine, adenosine, or the adenosine phosphates to the system interfere

### Table IV

<table>
<thead>
<tr>
<th>Flavin</th>
<th>Sarcosine</th>
<th>Dimethylglycine-( \alpha )-C&lt;sup&gt;14&lt;/sup&gt;</th>
<th>Dimethylglycine-( \alpha )-C&lt;sup&gt;14&lt;/sup&gt;H&lt;sub&gt;2&lt;/sub&gt;O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Riboflavin</td>
<td>10</td>
<td>9.4</td>
<td>12</td>
</tr>
<tr>
<td>Riboflavin phos-</td>
<td>9</td>
<td>8.2</td>
<td>10</td>
</tr>
<tr>
<td>phosphate</td>
<td>1</td>
<td>1.0</td>
<td>2</td>
</tr>
</tbody>
</table>

### Table V

<table>
<thead>
<tr>
<th>Quencher*</th>
<th>Oxygen uptake</th>
<th>CH&lt;sub&gt;O&lt;/sub&gt; isolated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Photometric</td>
<td>Formaldehyde/min</td>
</tr>
<tr>
<td></td>
<td>( \mu )moles</td>
<td>( \mu )moles</td>
</tr>
<tr>
<td>None</td>
<td>10</td>
<td>10.2</td>
</tr>
<tr>
<td>Adecyclacet</td>
<td>7</td>
<td>8.0</td>
</tr>
<tr>
<td>Adenosine</td>
<td>2</td>
<td>2.7</td>
</tr>
<tr>
<td>5-AMP</td>
<td>3</td>
<td>2.5</td>
</tr>
<tr>
<td>5-AMP, 1 ( \mu ) mole</td>
<td>6</td>
<td>6.5</td>
</tr>
<tr>
<td>ATP</td>
<td>3</td>
<td>3.5</td>
</tr>
<tr>
<td>Iodide</td>
<td>&lt;0.1</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>Thyroxine</td>
<td>&lt;0.1</td>
<td>&lt;0.2</td>
</tr>
</tbody>
</table>

* These compounds do not give rise to formaldehyde in the riboflavin phosphate system.
† Soluble with difficulty in buffer at pH 7.8.

Fig. 1. Rates of riboflavin phosphate-photooxidation of dimethylglycine (A) and sarcosine (B) as function of pH. Rates expressed as formaldehyde accumulation in 40 minutes.
with the catalytic action of riboflavin phosphate in the oxidation of sarcosine, as reflected in a depression of the oxygen uptake and formaldehyde accumulation. The adenine derivatives alone are not oxidized with riboflavin phosphate in our system. In similar experiments guanine and guanosine were also found to antagonize the photooxidation of sarcosine as judged by the formaldehyde analysis. However, with the latter purines in contrast to the adenine derivatives, there was a net increase in oxygen uptake which was shown to be due to the active photooxidation of guanine and guanosine themselves in the presence of riboflavin phosphate. The same was true for thymine, uracil, and cytosine. In further experiments it was found that other well established fluorescence quenchers such as iodide and thyroxine are also very efficient in hindering the photooxidative action of riboflavin phosphate.

From our studies thus far it may be deduced that riboflavin phosphate functions photocatalytically in the oxidation of amino compounds by the sequence of reactions depicted in Fig. 2 where the light-excited electronic state of the riboflavin phosphate has been designated as riboflavin P*. Although the inhibitory action of the purines, thymine, and pyrimidine, described in Table V, are compatible with a simple fluorescence quenching mechanism, such an antagonism alone does not suffice to characterize the lifetime of the excited electronic state of the riboflavin phosphate in its reaction with sarcosine or dimethylglycine and quantitative fluorometric studies are needed to answer this question. It should also be pointed out here that spectroscopic analyses of the reaction mixtures have failed to demonstrate any complex formation between riboflavin phosphate and sarcosine.

The temperature coefficient of the riboflavin phosphate-photooxidation of sarcosine, as measured by the rates of formaldehyde accumulation at 34 and 51°, was found to be 1.3. Compared with a Q10 of 2 to 4 for most thermochemical reactions, the low coefficient observed here implies that the higher temperature has merely increased the kinetic energy (diffusion rate) of the reacting molecules and has not enhanced their state of activation. That is to say, the light energy captured by the riboflavin phosphate system is apparently so large that any additional energy which could be supplied by a 10 20° increase in temperature is relatively insignificant.

**DISCUSSION**

The photochemical, nonenzymatic oxidation of sarcosine and dimethylglycine described above and the mitochondrial metabolism (3) of these same compounds both produce formaldehyde in high yields. However, the two oxidative pathways involve entirely different mechanisms. For example, with dimethylglycine and mitochondria, only the N-methyl groups are oxidized and yield active formaldehyde, which is subsequently converted to either free formaldehyde or serine β-carbon. The remainder of the dimethylglycine molecule can be recovered as sarcosine, glycine, or serine (4). In the photochemical decarboxylation and demethylation process, on the other hand, the N-methyl groups escape oxidation and no serine or glycine can be detected. In this case the formaldehyde is instead derived from the α-carbon. One possible mechanism for such an oxidation of dimethylglycine is described in Fig. 3. In the scheme depicted here, the production of carbon dioxide and the formaldehyde-dimethylamine intermediate has involved the loss of two electrons, one from the α-carbon and the other from either the carboxyl group or the nitrogen. Of the two latter alternatives the loss of an electron from the nitrogen would appear to be the more probable in view of our finding that the rate of photooxidation is increased when electrons are made available at the nitrogen atom (Fig. 1). The enzymatic reaction in which the α-carbon of glycine is oxidized to yield a precursor of the β-carbon of serine (5, 6) may proceed by way of a similar mechanism.

In addition to the possible use of these light-induced oxidations as models for enzymatic reactions, the prominent production of formaldehyde in many of these photooxidations also deserves some attention, particularly in the area of evolutionary chemistry. Such a consideration is especially pertinent since the participation of formaldehyde and its products in the evolution of biochemical systems has been underscored in theories of the origin of life (7). Moreover, the same compounds which we have found to be formaldehydogenic with riboflavin phosphate in light have been proposed as primordial compounds since they are found to be synthesized by an electric discharge through a gas mixture resembling the earth’s atmosphere in its early stages (8).

Also, these compounds are ubiquitous in all phyla, a fact which lends plausibility to the hypothesis that photodynamic

---

phenomena could be involved in evolutionary and mutagenic processes. If light played such a role, it is probable that compounds which possessed the ability to absorb light functioned as catalysts in primitive organized systems before the appearance of enzymes. Once established in primitive systems, these light-absorbing compounds may have continued to function catalytically even after the origin of proteins. It is perhaps significant in this regard that the respiratory coenzymes, except the pyridine nucleotides, can absorb visible light.

Entirely aside from these implications, however, the effects of photochemical reactions which we have described should sound a note of warning with respect to organic reactions in biological culture media. With complicated admixtures of compounds such as amino acids, metal sequestering agents, and others, together with flavins and their nucleotides, light might not only alter the composition of the media but could also induce untoward vectors of growth, differentiation, or mutation in the cells growing in such environments.

**EXPERIMENTAL**

Sarcosine-C\(^4\)H\(_2\) and sarcosine-C\(^14\)OOH were prepared in this laboratory by Dr. R. H. Abeles with procedures described elsewhere (10). The C\(^4\)H\(_2\)-methionine was kindly provided by Dr. Y. du Vigneaud. Dimethylglycine-\(\alpha\)-C\(^4\) was synthesized by the procedure of Michaelis and Schubert (11). \(N\)\'-ethyglycine and \(N\)\'-N-methylaniline were prepared by the method of Cocker (12). The sodium salt of glyoxylic acid was synthesized by the procedure of Metzler et al. (13). The commercial sources of cofactors and other compounds were as follows: riboflavin, Merck; riboflavin phosphate, sodium salt, monohydrate, Pabst Laboratories; FAD, Sigma "90", adenine, and the adenylic acids, Sigma; gua-}

---

3 An excellent illustration of the possible role of riboflavin in "natural" photodynamic phenomena is provided by the experiments of Galston's laboratory (9) which showed that the plant flavoprotein, indoleacetic acid oxidase, is light activated. Such a process would affect the titer of the growth hormone, indoleacetic acid, and suggests the possibility that riboflavin-sensitized photoresponses are implicated in plant growth and photosynthesis. Galston has also found that indoleacetic acid and related compounds are photooxidized with riboflavin in the absence of enzymes, but the nature of the oxidation products is still unknown.

uptake was 4 \(\mu\)moles. All of our analyses have been corrected for these "blanks." It should be pointed out that under our conditions the reaction solutions are still strongly fluorescent after 5 hours of illumination despite the photodecomposition of some riboflavin phosphate.

The total formaldehyde in the reaction flasks was measured spectrophotometrically (16). The radioformaldehyde was isolated with carrier as the dimedon derivative (17) and radiochromatograms as barium carbonate (17). Dimethylmalonate was recovered as the picrolinate salt (18), and was also isolated and identified by paper chromatography (19) in butanol, water, and acetic acid (4:5:1). This chromatographic system was also employed for the analysis of dimethylamine and sarcosine. Paper chromatographic analyses for glycine were carried out with phenol-water (4:1). In carrier analyses for radioglyoxylic acid the compound was isolated as the 2,4-dinitrophenylhydrazine derivative (18).

Absorption spectrum analyses to detect any possible complex formation between riboflavin phosphate and sarcosine in the buffered reaction mixtures were carried out in both the ultraviolet and visible regions with the Beckman model DU Spectrophotometer.

To determine the hydrogen peroxide in the reaction mixtures, a catalase solution was tipped into the main compartments of the Warburg flasks at the end of the experiment, and the evolved oxygen was measured manometrically.

**SUMMARY**

Riboflavin phosphate and riboflavin, in the presence of light, catalyze the nonenzymatic oxidation of sarcosine and dimethylglycine to carbon dioxide, formaldehyde, and the corresponding amine. Glycine is also oxidized in this system, with ammonia replacing the substituted amine as a reaction product, whereas betaine is inactive. Alanine and \(N\)\'-methylaniline are oxidized to yield acetaldehyde instead of formaldehyde in the photooxidation.

The origin of the reaction products as determined with \(C\(^14\)\)-labeled substrates can be formulated as follows, with sarcosine as an example:

\[
\begin{align*}
\text{Riboflavin P} + \text{H}_2\text{C}^-\text{NH}^-\text{CH}_2\text{--COOH} + \text{H}_2\text{O} & \rightarrow \\
\text{riboflavin P} - 2\text{H}^+ + \text{H}_2\text{C}^-\text{NH}^-\text{CH}_2\text{O} + \text{CO}_2 \\
\text{Riboflavin P} - 2\text{H} + \text{O}_2 & \rightarrow \text{riboflavin P} + \text{H}_2\text{O}_2
\end{align*}
\]

The methylaminoethanols and methylamines also yield formaldehyde in the presence of riboflavin phosphate and light, and as is the case with the glycines, their susceptibility to oxidation decreases in the following order of electronegativity of the amino group: tertiary > secondary > primary > quaternary. In view of its wide use in biochemical systems it is of particular interest that the tertiary amine, ethylenediaminetetraacetate, has been found to be a potent source of formaldehyde in this system.

Riboflavin phosphate fulfills a dual function in the foregoing reactions, serving both as the electron acceptor and, in its photoactivated state, as the source of activation energy for the dehydrogenations. Its photocatalytic action is inhibited by adenine derivatives, either when added separately to the riboflavin phos-
Catalysis of Oxidation by Flavin Coenzymes in Light

Vol. 234, No. 5

These reactions are discussed as models for enzyme reactions and also with regard to their implications in evolutionary chemistry.

REFERENCES

Catalysis of Oxidation of Nitrogen Compounds by Flavin Coenzymes in the Presence of Light
Wilhelm R. Frisell, Choong W. Chung and Cosmo G. Mackenzie


Access the most updated version of this article at http://www.jbc.org/content/234/5/1297.citation

Alerts:
- When this article is cited
- When a correction for this article is posted

Click here to choose from all of JBC's e-mail alerts

This article cites 0 references, 0 of which can be accessed free at http://www.jbc.org/content/234/5/1297.citation.full.html#ref-list-1