Superoxide-Facilitated Cathodic Cleavage of 1,1-Diphenyl Ketones

by

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Abstract

The cathodic conversion of 1,1-diphenylacetone (1) to benzophenone (2) was investigated. Through divided-cell electrolysers, cyclic voltammetry, and reactions with authentic superoxide, it was demonstrated that molecular oxygen is likely reduced to the superoxide anion at the cathode, where it proceeds to react with 1 to form an α-hydroperoxy ketone intermediate. Nucleophilic attack at the carbonyl by a second molecule of superoxide facilitates cleavage of the carbon-carbonyl bond to afford 2. Analogously, it was determined through mechanistic studies that α-substituted 1,1-diphenyl ketones undergo α-cleavage of the acyl group in a remarkably mild cathodic reaction. This transformation is postulated to occur via reduction of oxygen to superoxide, which forms a hydroperoxy anion that then attacks the carbonyl to give a tetrahedral intermediate. As the intermediate collapses to reform the carbonyl, the carbon-carbonyl bond is cleaved to yield the hydrocarbon product. Observed superoxide-facilitated α-cleavage offers an explanation for the previously-described cathodic cleavage of α-alkoxyaldehydes to benzhydryl alkyl ethers. The significant structural changes that are afforded by the mild cathodic reactions discussed here demonstrate the synthetic capabilities of organic electrochemistry.
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Introduction

Despite its long history as a synthetic method, organic electrochemistry is not widely utilized outside of the electrochemical or industrial communities.\(^1\) Electrosynthesis, however, bears several advantages over traditional forms of synthesis, not the least of is its inherently environmentally-friendly and economical nature. By carrying out a reaction on a substrate directly at the electrode, no reagents other than essentially mass-free electrons and supporting electrolyte is necessary.\(^2\) In some cases, even the need for supporting electrolyte can be eliminated through the use of ion exchange membranes or reusable ionic liquids.\(^3\) Organic electrosynthesis substitutes electric current for toxic oxidizing and reducing agents and reduces waste production by maximizing atom economy.\(^4\) The same electrochemical equipment can often be used to carry out oxidations and reductions, particularly in the use of undivided cells, which allow for simultaneous electrode processes.\(^5\) In addition, electricity is one of the cheapest redox reagents, and electrochemical reactions are often carried out at room temperature, under mild conditions, all of which lead to lower costs.\(^6\)

Besides the environmental compatibility and cost-effectiveness of electrosynthesis, the major rationale for conducting and studying organic electrochemical reactions is that there are many reactions that can only be achieved through electrochemical processes.\(^5\) Many chemical transformations that require multiple steps and harsh conditions using conventional methods can be afforded in one-pot, high-yielding electrochemical syntheses. These reactions can also be made more selective by carefully controlling the applied potential or the magnitude of
current passed through solution. The research and results presented in this thesis illustrate the synthetic capabilities, and ultimately the value, of organic electrochemistry.

The focus of this research is two-fold. The primary emphasis is on the investigation of the mechanistic pathway through which the cathodic conversion of 1,1-diphenylacetone (1) to benzophenone (2) occurs. In addition, the cathodic cleavage of α-substituted 1,1-diphenyl ketones to their corresponding hydrocarbons was examined. Our interest in these mechanisms originates from previous work done in the Fry group on the anodic oxidation of diphenylacetaldehyde (3) in the presence of various nucleophiles. Rachel Merzel showed that 3 can be converted to 2 through both aerobic and electrochemical means. It was postulated that the oxidation of 3 by molecular oxygen occurs by the [2+2] cycloaddition of oxygen across the enol tautomer of 3 (3a) to form a 1,2-dioxetane species (4). 4 is then thought to decompose via the simultaneous cleavage of both the O-O and C-C bonds to yield benzophenone (Scheme 1).
Scheme 1. Proposed mechanism for the oxidation of 3 by molecular oxygen.

The alternative electrochemical pathway through which 3 is converted to 2 was investigated through the controlled-potential electrolysis of 3 in the presence of water. Preliminary results indicated that 3 was converted to 2 through a stable intermediate that was later identified as α-hydroxydiphenylacetaldehyde (5), formed from the nucleophilic attack by water on the carbocation intermediate that is generated when a π-bonding electron is removed from 3a. The reaction was repeated in the presence of 18O-labeled water to confirm whether nucleophilic attack by water is responsible for the conversion of 3 to 2. GC-MS analysis showed electrochemical incorporation of 18O into both 5 and 2, which supported the proposed mechanism for the electrochemical conversion of 3 to 2 shown below (Scheme 2).
Scheme 2. Proposed anodic oxidation of 3 to 2 in the presence of water.

The mechanistic pathway for the conversion of 3 to 2 was postulated to involve the removal of a π-bonding electron from 3a to form a radical cation thought to be stabilized by the two phenyl groups. It is believed that the cation would be
attacked by water as a nucleophile, and further oxidation would remove another electron to form a new carbocation. This species could then undergo nucleophilic attack by another molecule of water to yield a tri-hydroxy intermediate that could quickly decompose to form α-hydroxydiphenylacetaldehyde (5) observed in the GC-MS spectra. Further anodic oxidation of 5 may result in formation of 2.

Analogously, it was hypothesized that anodic oxidation of 3 in the presence of various alcohols would result in a similar nucleophilic attack to produce the corresponding hemiacetal species that dissociates to form the α-alkoxyaldehyde (6). Merzel demonstrated that electrochemical oxidation of 3 in different alcohols did result in an α-alkoxyaldehyde intermediate that was unexpectedly decarbonylated to yield the corresponding benzhydryl alkyl ether (7) (Scheme 3). This was the beginning of a line of inquiry that led to the determination that the conversion of 3 to 7 occurs through two competing pathways: direct α-cleavage of the carbon-carbonyl bond of 3, followed by nucleophilic attack by the alcohol, or anodic oxidation of the enol of 3 in a pathway comparable to the proposed mechanism for the conversion of 3 to 2 in water. It was concluded that at least 60%, but probably a much higher percentage, of the oxidation of 3 to 7 occurs via the enolic pathway due to the appreciable amount of enol content of 3 available in solution.
Scheme 3. Electrochemical conversion of diphenylacetaldehyde (3) to benzhydryl ether via the enolic pathway.

In a related study, Boris Sheludko of the Fry group showed that 1,1-diphenylacetone (1) undergoes the same conversion, in the presence of various alcohols, to 7. In contrast to the preferred enolic pathway through which diphenylacetaldehyde (3) proceeds, 1 is converted to 3 via direct α-cleavage (Scheme 4), at least 86% of the time, and the enol is only minimally involved.10
Scheme 4. Electrochemical conversion of 1 to benzhydryl ethers (7) via the keto pathway (direct α-cleavage).

These mechanisms came into question, however, when Sheludko placed α-cyclohexoxy-1,1-diphenylacetone (8), a possible intermediate of the conversion of 1 to benzhydryl cyclohexyl ether (9) via the less-preferred enolic pathway, into the cathode compartment of a divided cell. The results indicated complete conversion of 8 to 9, which forced us to rethink all proposed mechanisms regarding the conversion of 1 and diphenylacetaldehyde (3) to corresponding benzhydryl ethers (7). All data obtained up to this point resulted from electrolyses performed in an undivided cell. It was postulated that anodic oxidation is responsible for the generation of 7, but it had to be considered that participation from both electrodes may actually be involved in a process Manuel Baizer termed “paired electrosynthesis”.11
In addition, Evan Baum of the Fry group showed that α-cyclohexoxydiphenylacetaldehyde (10) was rapidly converted to 9 when placed in the cathode compartment of a divided cell, but neither 8 nor 10 experienced any conversion to 9 when they were placed in the anode compartment.\textsuperscript{12}

![Scheme 5] Electrochemical conversion of 8 and 10 occurs at the cathode, not the anode.

The conversion of 10 to 9 at the cathode was unexpected and suggests that the mechanism for the conversion of diphenylacetaldehyde (3) to the corresponding benzhydryl ethers is more complex than previously anticipated. The results from Merzel’s experiments show clear conversion of 3 to 10 at the anode, which led us to initially assume that anodic oxidation of 10 generated the ether 9.\textsuperscript{8} However, the divided-cell experiments described in Scheme 5 disprove this hypothesis and provide
evidence for a new mechanistic pathway in which anodic oxidation of the enol tautomer of 3 results in a hemiacetal species that loses an alcohol to form the corresponding α-alkoxyaldehyde (6), which then migrates to the cathode, where it is decarbonylated to the 7 (Scheme 6).

Scheme 6. Anodic oxidation of 3 to 6, followed immediately by cathodic reduction to 7.

To further investigate this unprecedented mild cathodic cleavage of α-alkoxyaldehydes and α-alkoxyketones, another control experiment was carried out. As stated earlier, Sheludko demonstrated that the preferred pathway for the conversion of 1,1-diphenylacetone (1) to the corresponding benzhydryl ethers (7) involves direct α-cleavage of the carbon-carbonyl bond, rather than oxidation of the enol tautomer. Because this pathway bypasses formation of an α-alkoxyketone intermediate, 1 is expected to be cleaved at the anode and then attacked by the nucleophile in solution. Therefore, the conversion of 1 to the ethers is still expected to
be an anodic transformation. As a control electrolysis, 1 was placed in the cathode compartment of a divided cell in the absence of an alcohol, and the results were surprising. 1 showed rapid and complete conversion to benzophenone (2) (Scheme 7). Since 2 is at a higher oxidation state than 1, it seems to suggest that an electrogenerated oxygen species, such as superoxide, may be acting as a nucleophile and attacking the carbonyl group of 1 to form 2.13

![Scheme 7](image)

**Scheme 7.** Electrochemical conversion of 1 to 2 at the cathode.

Based on the results from this experiment, we postulated that a dioxygen species formed from the cathodic reduction of molecular oxygen is responsible for the cleavage observed when α-alkoxyaldehyde is converted to the benzhydryl ether at the cathode. The Fry group had shown earlier that the carbon-silicon bond of α-dimethylsilyl esters are cleaved by electrochemically-generated superoxide.14 It was considered that a similar process may be at play here. Therefore, in order to develop a comprehensive mechanism for the conversion of diphenylacetaldehyde (3) in the presence of various alcohols to the corresponding benzhydryl ethers, the role of oxygen in the cathodic conversion of 1 to 2 was investigated.
Results

A. Mechanistic Studies of the Cathodic Oxidation of 1,1-Diphenylacetone to Benzophenone

I. Initial Work

Based on the results of the divided-cell experiments conducted by Boris Sheludko and Evan Baum, it was decided that two control experiments be carried out before any further studies are made to probe the mechanism for the cathodic transformation of 1,1-diphenylacetone (1) to benzophenone (2).

**Attempted Autoxidation of 1,1-Diphenylacetone (1).** The first experiment was designed to test for the autoxidation of 1 to control for possible aerobic oxidation of 1 to 2 in a mechanistic pathway similar to the conversion of diphenylacetaldehyde (3) to 2. The reaction was carried out in a 25 mL three-neck round bottom flask equipped with a stir bar and air inlet over the course of three weeks. Atmospheric oxygen was continually bubbled into solution during this period, and dry electrolyte solvent was replenished as needed. GC-MS analysis at the end of the three weeks showed that 1 was the major component in solution. The gas chromatogram exhibits one prominent peak, with a mass spectrum containing a parent peak of m/z 210 and a large fragment at m/z 167. This mass spectral data corresponds to the spectrum for pure samples of 1, which suggests that 1 is stable in the presence of molecular oxygen, presumably because oxidation would proceed via the enol, and is unlikely to oxidize to 2 in a mechanism similar to the autoxidation of 3.

**Constant Current Electrolysis of 1,1-Diphenylacetone (1) in the Presence of 2-Phenylethanol at the Anode.** In order to confirm that 1 proceeds to benzhydryl
ethers (7) at the anode, 1 was placed in the anode compartment of a divided cell in the presence of 2-phenylethanol. A constant current electrolysis was carried out at 25 mA under nitrogen-purged conditions, and 1 proceeded cleanly to benzhydryl phenethyl ether (11) with a small amount of unreacted 1 left over (Figure 1). The mass spectrum of the major product in solution after four hours shows a parent peak of m/z 288, the expected molecular weight of 11, and peaks of m/z 183, 167, and 152, which all correspond to the fragmentation pattern for 11 reported in Sheludko’s work.10

![Figure 1](image)

**Figure 1.** Gas chromatogram of the conversion of 1 to 11 after four hours.

Several implications emerge from these results. The conversion of 1 to 11 exclusively at the anode indicates that this transformation is indeed an oxidative process, providing further evidence that 1 undergoes α-cleavage, rather than proceeding via its enol (See Discussion for further details on the conversion of 1 to benzhydryl ethers). This mechanistic pathway differs from the postulated conversion
of diphenylacetaldehyde (3) to benzhydryl ethers (7), which is believed to involve participation from both electrodes. Preliminary results found that 1 was converted to 2 at the cathode, which suggests that oxygen may be the species that is being reduced to either the superoxide or peroxide ion (or both) and subsequently attacking 1 to form a hydroperoxy intermediate. The latter is then expected to decompose to 2. What is of interest regarding this hypothesized pathway is that a hydroperoxy intermediate may account for the cathodic cleavage of α-alkoxyaldehyde (6) to 7. To determine whether oxygen plays a central role in the conversion of 1 to 2, and analogously in the cleavage of 6, several electrolyses in the absence and presence of oxygen were carried out. The results obtained from these experiments are detailed in the next section.

II. Electrolyses in the Absence and Presence of Oxygen

The following electrolyses were carried out to determine the effect oxygen has on the cathodic conversion of 1 to 2. All three experiments required the use of a divided cell containing a stir bar, air inlet, and 0.1M Bu₄NBF₄ in CH₃CN as the dry electrolyte solvent. The conducting gel used to separate the anode and cathode compartments was synthesized using methylcellulose-saturated DMF containing 0.1M Bu₄NBF₄ heated to 150°C and poured onto a fritted disk membrane. The counter and working electrodes were each prepared by threading a platinum wire through a piece of 2 cm by 2 cm carbon cloth. In each electrolysis, 2.7 mmol of 1 was used, and the current was kept at a constant 25 mA for the duration of the reaction. The experiments were comprised of (a) an electrolysis carried out under nitrogen, (b)
an electrolysis carried out under atmospheric oxygen, and (c) the reaction between 1 and pre-electrolyzed oxygen.

**Constant Current Electrolysis of 1,1-Diphenylacetone (1) under Nitrogen at the Cathode.** After it was postulated that oxygen may be involved in the cathodic conversion of 1 to 2, it was decided that a divided-cell electrolysis be run under nitrogen in an attempt to bubble out as much oxygen as possible from the solution. If oxygen is completely absent from the reaction mixture, the successful electrochemical generation of 2 indicates that oxygen is not involved in the conversion of 1 to 2. Under these conditions, if 2 does not form, oxygen may be a crucial reagent in the conversion discussed here. Prior to turning on the current, nitrogen was bubbled into the electrolyte solution containing 1 for 30 minutes, and once the current was turned on, the nitrogen needle was pulled out of solution but continued to inject nitrogen into the flask for the remainder of the reaction. The progress of the reaction was monitored every 30 minutes by GC-MS analysis. Figure 2 shows the progression of the conversion of 1 to 2 at 30 minutes, 120 minutes, and 270 minutes. By 30 minutes, a small amount of 2 had already formed. During the course of the reaction, as more and more 1 was converted to 2, a small amount of a possible intermediate compound (A), with a GC retention time of 11.49 minutes, and intermediate compound (B), with a GC retention time of 10.98 minutes, had formed. By 120 minutes, a small amount of compound B can be seen in the gas chromatogram in Figure 2, but in other trials of this experiment, a much larger peak with a retention time and fragmentation pattern corresponding to compound B can often be seen. By 270 minutes, compound A and B had both disappeared from solution. What was
surprising was the appearance of another compound (C), with a retention time of 9.05 minutes, after all of 1 had been consumed.

The mass spectrum of compound A (Figure 3a) contains a parent peak of m/z 210 and large peaks of m/z 183, 167, and 105. It was postulated at first that compound A could be 1,3-diphenylacetone (12), but comparison with the mass spectrum of commercially available pure samples of 12 indicated that A is not 12. The presence of peak m/z 167 indicates a fragment resembling the loss of the carbonyl group of 1 via α-cleavage, providing strong evidence that A contains both phenyl groups bonded to a benzylic carbon. High intensity peaks of m/z 183, 105, and 77 are reminiscent of the mass spectra for 2, with the peak of m/z 183 possibly corresponding to protonated benzophenone. This evidence suggests that A may be an intermediate containing oxygen bonded to the α-carbon, quite possibly α-hydroperoxydiphenylacetone (13). According to Sawaki and Ogata, 13 is an unstable species. The parent peak of m/z 242 may not be observable with the next highest intensity peak being m/z 210, generated from the cleavage of the carbon-oxygen bond. Without having isolated A and obtained the necessary 1H and 13C NMR, however, it is impossible to confirm the identity of A.
Figure 2. Gas chromatograms showing the progression of 1 to 2 at the cathode under nitrogen-purged conditions.
Figure 3. Mass spectra of a) compound A, postulated to be an α-hydroperoxy intermediate; b) compound B, verified as benzhydryl acetate (14); c) compound D, confirmed to be diphenylmethane (16).
Compound B with a parent peak of \( m/z \) 226 was hypothesized to be benzhydryl acetate (Figure 3b). In order to fully identify and characterize B, benzhydryl acetate (14) and methyl diphenylacetate (15) were synthesized using alternative methods, and the authentic samples obtained were injected in the GC-MS instrument to obtain mass spectra for comparison. Implementing a Fischer esterification procedure, acetic anhydride was added to benzhydrol and catalytic amounts of concentrated sulfuric acid in a test tube. The mixture was then heated for 38 minutes to yield 14.\textsuperscript{17} GC-MS and \(^1\)H NMR analysis confirmed that the product obtained from this synthesis was 14, and upon comparison of the mass spectrum of 14 (Figure 4) to that of B, it was determined that the retention time and fragmentation pattern of both spectra were the same. B was, therefore, identified as 14.

\[ \text{GC-MS and } ^1\text{H NMR analysis} \]

![Mass spectrum of benzhydryl acetate 14.](image)

To ensure that we can rule out the possibility of B being methyl diphenylacetate (15), which also has a molecular weight of 226, the synthesis of 15 was carried out by adding diphenylacetic acid to an excess of methanol containing
catalytic amounts of sulfuric acid. The mixture was refluxed overnight, and a sample was worked up and injected in the GC-MS instrument for analysis. The peak corresponding to 15 has a retention time of 11.284 minutes, which is different from the retention time for compound B. Additionally, the fragmentation pattern displayed by the mass spectrum of 15 contains a significant peak of \( m/z \) 167 that is absent in the mass spectrum for B. Moreover, the mass spectrum of B has significant peaks of \( m/z \) 166, 165, 105, and 77 that are absent from the mass spectrum of 15. It was, thus, determined conclusively that compound B was not 15 but most likely 14.

It was surprising when a peak corresponding to compound C started to appear in the gas chromatogram of the conversion of 1 to 2 after all of 1 had been consumed. The mass spectrum of C (Figure 3c) contains a parent peak of \( m/z \) 168 and significant peaks of \( m/z \) 167, 153, 152, and 91. It was postulated that C was diphenylmethane (16), which has a molecular weight of 168 and often is a byproduct in electrolyses containing 1. A sample of commercially-available 16 was injected into the GC-MS instrument, and the retention time and fragmentation pattern of 16 was identical to that of C, corroborating our hypothesis that C was 16. This result suggests that 16 is forming alongside 2.

Although the formation of benzophenone (2) may indicate that oxygen is not involved in the oxidation of 1 to 2, it cannot be ignored that despite efforts to exclude atmospheric oxygen from the reaction flask, oxygen was ultimately able to diffuse into solution. The flask (Figure 39, Page 87) is built in such a way that the anode compartment is exposed to air. Because the conducting gel separating the anode and cathode compartments was not prepared in an oxygen-free area, it can also be
assumed that the gel contains oxygen. In this way, even though nitrogen was bubbled in solution for 30 minutes prior to turning on the current and for the duration of the reaction, oxygen can still be diffusing into solution from the anode.

**Constant Current Electrolysis of 1,1-Diphenylacetone (1) under Atmospheric Oxygen at the Cathode.** After carrying out an electrolysis of 1 under nitrogen, it was decided that another electrolysis be carried out under atmospheric oxygen to test whether there are any changes to the progression of 1 to 2. Prior to turning on the current, oxygen was bubbled into the electrolyte solution for 20 minutes. Once the current was turned on, the needle was pulled above solution and continued to introduce air into the flask for the duration of the electrolysis. The progress of the reaction was monitored periodically by GC-MS. Figure 5 shows the progression of the reaction at 60 minutes, 157 minutes, 205 minutes. Much like the constant current electrolysis of 1 under nitrogen, as 1 was consumed, possible intermediates A and 14 appeared with the simultaneous formation of 2. A significant difference from the electrolysis of 1 under nitrogen was that by 157 minutes, the reaction had almost reached completion, and by 205 minutes, all starting material and possible intermediates had been consumed with only major product 2 observable in the gas chromatogram. The conversion of 1 to 2 was sped up with oxygen continuously being injected into the reaction flask, suggesting that the addition of oxygen may be making the reaction go faster and providing evidence that oxygen is a reagent in the conversion of 1 to 2. Another difference that is worth noting in the progression of 1 to 2 is that a peak corresponding to compound C, which was identified to be diphenylmethane (16), was absent from the gas chromatogram taken
at 205 minutes after the reaction had gone to completion. 16 did not appear at any
time during the course of the reaction, implying that 16 is a byproduct that does not
appear under oxygenated conditions.

Figure 5. Gas chromatograms showing the conversion of 1 to 2 under atmospheric
oxygen.
Reaction of 1,1-Diphenylacetone (1) with Pre-Electrolyzed Oxygen.

Assuming the conversion of 1 to 2 is facilitated by a dioxygen species generated at the cathode that goes on to react with 1, reducing oxygen-saturated electrolyte solution, turning off the current, and adding 1 will also result in formation of 2. Based on this assumption, another electrolysis was carried out by bubbling oxygen for 30 minutes into the dry electrolyte solvent in the cathode compartment of a divided cell. Like in the last reaction, the needle was pulled above the solution but continued to inject air into the reaction flask for the duration of the reaction. The current was turned on at 25 mA for 200 minutes, approximately the same amount of time it took to convert 1 to 2 in the previous reaction. Once the current was turned off, 1 was placed into the cathode compartment and a sample was immediately taken out to be analyzed by GC-MS. The gas chromatogram at 0 minutes in Figure 6 already shows a small peak with a retention time and fragmentation pattern corresponding to those of 2. The results obtained from the attempted autoxidation of 1 prove that 1 does not convert to 2 in just the presence of molecular oxygen, even in three weeks. Therefore, the formation of 2 in this reaction most likely results from reducing oxygen into another dioxygen species that then reacts with 1. After 40 hours of stirring 1 in the electrolyte solution, a sample was taken and analyzed by GC-MS to give a spectrum showing predominately starting substrate 1. Although the peak corresponding to 2 had grown, it did not grow significantly over the course of this period, which indicates that whatever dioxygen species is responsible for the conversion of 1 to 2 is not stable in solution for long periods of time. This may also suggest that continuous generation of this species in situ may be necessary to drive the reaction to completion.
III. Cyclic Voltammetry

The cyclic voltammetry experiments reported in this section were carried out to elucidate the electrochemical conversion of 1 to 2 under nitrogen-purged and oxygenated conditions. The experiments were performed in a 10 mL solution of 0.1M Et₄NBF₄ in acetonitrile at a scan rate of 0.1 V/s, using a silver wire in 0.1 M silver
nitrate acetonitrile solution as the reference electrode, glassy carbon as the cathode, and a platinum wire as the anode. All scans were executed from left to right, with reduction occurring during the first scan and oxidation occurring during the reverse scan.

The first cyclic voltammogram (CV) obtained was done with 1,1-diphenylacetone (1) dissolved in the electrolyte solution, which was bubbled with nitrogen for 20 minutes prior to the first scan in order to remove as much oxygen as possible. The CV in Figure 7 shows no major reduction peak in the region analyzed, implying that nothing in solution, including 1, can be reduced at the potential here.

![Cyclic voltammogram of 1 under nitrogen-purged conditions.](image)

**Figure 7.** Cyclic voltammogram of 1 under nitrogen-purged conditions.

In order to compare the reduction of 1 under nitrogen-purged conditions and under oxygenated conditions, the reaction mixture was exposed to air for 20 minutes to allow atmospheric oxygen to dissolve into solution. A CV was then taken of the
same mixture containing 1 and, presumably, now oxygen. Figure 8 shows the CV of 1 under nitrogen-purged and oxygenated conditions overlaid on top of each other. What is significant about the reduction of 1 under oxygenated conditions is the presence of a large peak at -1.3V and another peak at -2.3V, which were both absent under nitrogen.

Figure 8. The red wave shows the CV of 1 under nitrogen, and the black wave shows the CV of 1 under oxygen.

Because oxygen is known to be the easiest species to be reduced, it was postulated that the large peak at -1.3V corresponded to the reduction of oxygen. Following this line of reasoning, 10 mL of electrolyte solvent containing no 1 was exposed to atmospheric oxygen for 20 minutes before it was analyzed by cyclic voltammetry. The resulting CV obtained displayed a large reduction peak at -1.3V but no second reduction peak at -2.3V. The CV of this trial was overlaid on top of the CV
of the previous experiment for comparison, and it is clear that the large peak at -1.3V is a result of the reduction of molecular oxygen (Figure 9).

![Graph showing CV of atmospheric oxygen and CV of 1 under oxygen](image)

**Figure 9.** The red wave shows the CV of atmospheric oxygen, and the black wave shows the CV of 1 under oxygen.

**Figure 7** shows no reduction peak corresponding to 1 in the region analyzed, which suggests that 1 cannot be reduced at any potential from 0V to -3.0V. The peak that is appearing at -2.3V in the CV of 1 under oxygen must, therefore, be the reduction of another species in solution. Benzophenone (2) is known to exhibit two reduction waves in acetonitrile—one that begins at -1.2V and the other that begins at -2.0V. Based on this information, it was decided that a sample of electrolyte solvent containing dissolved pure 2 be analyzed. The solution was exposed to atmospheric oxygen prior to the first scan. The red wave displayed in **Figure 10** is the CV obtained from the reduction and oxidation of 2 under oxygen. The oxygen reduction
peak at -1.3V is shown along with another reduction peak at -2.3V. Comparison to the CV of the reduction and oxidation of 1 under oxygen provides strong evidence that the reduction peak at -2.3V is indeed the reduction of 2.

![Graph](image_url)

**Figure 10.** The red wave shows the CV of 2 under oxygen, and the black wave shows the CV of 1 under oxygen.

To check that the peaks corresponding to 2 and the species produced from 1 occur at the same potential under oxygenated conditions, both 1 and 2 were placed in a fresh solution of Et$_4$NBF$_4$ in acetonitrile. Air was allowed to dissolve into solution prior to the first scan. The CV (Figure 11) obtained displayed similar results to previous scans, with a large oxygen reduction peak at -1.2V, a large peak at -2.3V, and no other major peak in the region scanned. Of interest, however, is that the peak at -2.3V, postulated to correspond to the reduction of 2, is at least twice as large in this CV than in previous voltammograms, possibly due to the presence of both
commercially-available 2 placed in solution and 2 produced in situ from 1 during the course of the first scan.

![Cyclic voltammetry graph]

**Figure 11.** The red wave corresponds to the CV of 1 and 2 under oxygen, and the black wave corresponds to the CV of just 1 under oxygen.

The cyclic voltammetry experiments described here provide strong evidence for the conversion of 1 to 2 via a dioxygen species generated from the reduction of oxygen in solution. It appears that 2 forms rapidly after the reduction of oxygen as demonstrated by the presence of a peak corresponding to the reduction of 2 in just the first reduction wave. It is also worth remembering that there is no peak at -2.3V under nitrogen-purged conditions, which indicates that only under oxygen is the species that is being reduced at this potential being formed. With the confirmation that oxygen is involved in the conversion of 1 to 2, it was decided that the identity of the dioxygen species be pinpointed by reacting 1 with authentic superoxide and peroxide.
IV. Chemically-Generated Superoxide and Peroxide Reactions

The results reported in this section were obtained from various experiments involving potassium superoxide (KO₂) and sodium peroxide (Na₂O₂), used here as chemical sources of possible dioxygen species produced from the reduction of oxygen in the electrochemical conversion of 1,1-diphenylacetone (1) to benzophenone (2). If the addition of KO₂ or Na₂O₂ to a solution of 1 results in the formation of 2, a dioxygen species, either superoxide or peroxide or both, is responsible for the electrochemical conversion of 1 to 2 at the cathode. All reactions followed the procedure outlined by Shukla and Singh and were carried out using a 5:2.5:1 ratio of KO₂:Et₄NBr:substrate unless otherwise noted.¹⁹

Reaction of 1,1-Diphenylacetone (1) with KO₂. In order to determine whether superoxide plays a role in the electrochemical conversion of 1 to 2, KO₂ and Et₄NBr were added to 35 mL anhydrous DMF in a 100 mL three-neck round bottom flask. After allowing the mixture to stir for 15 minutes to facilitate the phase transfer of superoxide to the organic layer, 1 was added to solution. The reaction took 18 hours to reach completion, after which analysis by TLC showed the presence of one large spot and no spots corresponding to starting material. Analysis by GC-MS showed the presence of only one peak with a retention time of 10.415 minutes (Figure 12). The mass spectrum of this peak has a parent peak of $m/z$ 182 and significant peaks of $m/z$ 105 and 77. This fragmentation pattern agrees with the mass spectrum obtained from injecting a sample of authentic 2 in the GC-MS instrument. 2 has a molecular weight of 182, which is reflected by the parent peak of $m/z$ 182, and the peak of $m/z$ 105 corresponds to the loss of a phenyl group while 77 is the mass of
a phenyl fragment. The gas chromatogram of the product obtained in this reaction also shows that the yield of 2 from the reaction between 1 and superoxide is high with 100% yield as determined by GC-MS analysis.

**Figure 12.** Gas chromatogram and mass spectrum of the product obtained from reacting 1 with KO₂.
The product was worked up by using saturated NaCl and sodium bicarbonate solution to decompose unreacted superoxide. Benzophenone (2) was extracted using diethyl ether, dried, and isolated to give a crude yellow oil, which was further purified using flash chromatography. The $^1$H NMR spectrum for the final product is shown below in Figure 13. The multiplet in the region from 7.40 ppm to 7.80 ppm can be attributed to the ten aromatic protons, while the small peak at 7.26 ppm is due to the residual chloroform peak. Two other signals, one integrating for 0.48 proton at 1.63 ppm and the other integrating for 0.44 proton at 1.26 ppm, can be assigned to water and hexanes, respectively. It is reported in literature that hexanes displays a peak at 1.26 ppm. Hexanes was used in the 95:5 hexanes:ethyl acetate elution solvent in the flash chromatography step of the purification process, and it is not surprising that some hexanes is still left over in the product. The low integration of both peaks also indicates that the solvents are minor impurities in the final product. $^1$H NMR analysis suggests that 2 was indeed formed from the reaction of 1 with superoxide.
Figure 13. $^1$H NMR spectrum of the product obtained from the reaction of 1 with superoxide. Besides solvent impurities, the spectrum shows that the product is 2.

**Reaction of Diphenylacetaldehyde (3) with KO$_2$.** Rachel Merzel’s work in the Fry group has shown that diphenylacetaldehyde (3) produces 2 through aerobic and electrochemical methods.\(^8\) To investigate whether 3 reacts with KO$_2$ in a similar manner, 3 was placed in a three-neck round bottom flask containing dissolved KO$_2$ and Bu$_4$NBr in anhydrous DMF and allowed to react, with stirring and under nitrogen, for 13 hours. A sample was worked up and injected into the GC-MS instrument for analysis. The gas chromatogram (Figure 14) shows one prominent peak with a retention time of 10.415 minutes and a mass spectrum with a parent ion peak of $m/z$ 182. In addition to the corresponding retention time and parent ion, the mass spectrum of the product exhibits a fragmentation pattern, with significant peaks
of $m/z$ 105 and 77, characteristic of 2. The formation of 2 here demonstrates the ability of superoxide to react with 3, cleaving the carbon-carbonyl bond through chemical rather than electrochemical methods. Although it was possible that 3 reacted with molecular oxygen to form 2 via an aerobic oxidative pathway, Merzel has demonstrated that in three days, GC-MS results show only approximately 21% conversion of 3 to 2. In 13 hours, however, 3 had already fully converted to 2 based on the GC-MS spectrum obtained from this experiment. Taking into account possible reaction with atmospheric oxygen, a significant amount of 3 is still converted to 2 in a short amount of time, implying that superoxide is primarily responsible for converting 3 to 2.

**Figure 14.** Gas chromatogram of the reaction of 3 with KO$_2$. 
Reaction of 1,1-Diphenylacetone (1) with Na$_2$O$_2$. The chemical conversions of 1 and 3 to 2 discussed thus far have used KO$_2$, namely superoxide, as the key reagent, but superoxide is not the only dioxygen species that can form from the reduction of oxygen. Cathodic reduction of oxygen results in the formation of superoxide, peroxide, hydroperoxyl radical, and hydrogen peroxide.$^{13b}$ We have been making the assumption thus far that only superoxide is responsible for reacting with 1 or 3 to form a possible $\alpha$-hydroperoxy ketone intermediate that decomposes into 2. It was therefore decided that 1 be placed in a three-neck round bottom flask containing five equivalents of Na$_2$O$_2$ and two and a half equivalents of Bu$_4$NBr in DMF. The same procedure from Shukla and Singh was utilized in this experiment except Na$_2$O$_2$ was used as the primary dioxygen source rather than KO$_2$.\textsuperscript{19} 1 was allowed to stir with Na$_2$O$_2$, and samples were worked up and analyzed using GC-MS after 24 hours, 72 hours, and two weeks (Figure 15). At 24 hours, most of starting material 1, with a retention time of 11.033 minutes, had not yet reacted. A small peak on the mass spectrum, with a retention time of 10.402 minutes, is observable, however. The parent ion peak of $m/z$ 182 and its fragmentation pattern coincides with what is expected for 2, which indicates that 1 can be converted to 2 via a chemical pathway with peroxide. At 72 hours, more of starting material 1 has been converted to 2, but the reaction is still far from reaching completion. After two weeks, a sample was injected into the GC-MS instrument, and the spectra obtained indicate full conversion of 1 to 2.
Figure 15. Gas chromatograms showing the progression of the reaction of 1 with Na$_2$O$_2$. 
There is, however, another peak with a retention time of 12.733 minutes that has a parent ion peak of \( m/z \) 214. Other significant peaks in the mass spectrum are \( m/z \) 197, 180, 167, and 139. Without having isolated this compound and analyzed it using \(^1\)H or \(^{13}\)C NMR, it is difficult to characterize it. This experiment does demonstrate that peroxide reacts with 1 to afford 2 but at a much slower rate than does superoxide.

**V. Further Mechanistic Studies**

Various experiments described in the above sections indicate that oxygen is a reagent in the conversion of 1,1-diphenylacetone (1) to benzophenone (2), but the details of this mechanism are still unknown. Based on the intermediates and byproducts observed in the GC-MS spectra of the electrolysis of 1 under nitrogen, it was decided that further experiments involving benzhydryl acetate (14) and diphenylmethane (16) be carried out to clarify possible steps of the mechanism. These experiments include the cathodic reductions of 14 and 16.

**Cathodic Reduction of Benzhydryl Acetate (14).** As described in Section AII, a small peak corresponding to 14 was observed in the gas chromatograms of the cathodic electrolyses of 1 under nitrogen and atmospheric oxygen. Although the 14 peaks reported in this thesis were small, several other trials of the electrolysis of 1 under nitrogen exhibited much larger peaks of 14 that disappear as the reaction continues, indicating that 14 may be significant to the conversion of 1 to 2. To test whether 14 is an intermediate in the conversion of 1 to 2, 14 was placed in the cathode of a divided cell containing dry electrolyte solution, and the current was turned on at 25 mA. GC-MS analysis revealed that at 60 minutes, no major conversion of 14 to other compounds observable in the gas chromatogram was seen.
At 120 minutes, most of starting material 14 was still present in solution, but two peaks, with a retention time of 8.278 minutes (E) and 9.171 minutes (F), were observed. By 240 minutes, all of 14 had disappeared but peaks corresponding to compound E, compound F, and compound G, which has a retention time of 10.565 minutes, could be detected.

**Figure 16.** Gas chromatograms of the cathodic electrolysis of 14 at 120 minutes and 240 minutes.

Not much conversion of 14 to products discernible in the gas chromatogram occurred until 120 minutes into the electrolysis. At this point, a peak corresponding to compound E is clearly visible. The mass spectrum of E shows a parent ion peak of
m/z 429 and significant peaks of m/z 341, 325, 207, and 147. It is unlikely that a compound with such a low retention time (8.278 minutes) would have a molecular weight of above 300 g/mol, which suggests that there may have been some impurity still left on the column prior to injection of the electrolysis sample. Without having worked up the reaction and separated the compounds, it is impossible to identify compound E.

The peak corresponding to compound F became visible by 120 minutes and continued to grow in size until it became the primary component of the sample injected into the GC-MS instrument at 240 minutes. Analysis of the mass spectrum of F revealed that there is a parent ion peak of m/z 168 and significant peaks of m/z 167, 153, and 152—a fragmentation pattern that matches that of diphenylmethane (16). The similar retention time also provides support for identifying F as 16. The reduction of benzhydryl acetate (14) to 16 suggests that it is very likely that 14 is being converted to 16 in the gas chromatograms of the conversion of 1 to 2 under nitrogen, offering a possible explanation for the appearance of 16 as 1 reacts to form 2. Further details will be provided in the Discussion section.
Figure 17. Mass spectrum of compound F, hypothesized to be 16.

Of the most interest, however, was the peak corresponding to compound G, which has a similar retention time to that of 2. The mass spectrum of G shows a parent ion peak of m/z 182, and its fragmentation pattern matches that exhibited by 2. The appearance of 2 in the reduction of 14 is unexpected but may suggest that 14 is a very minor contributor to the formation of 2 in the cathodic conversion of 1 to 2. Because the major product of the reduction of 14 is 16, it is unlikely that the former is an intermediate in the conversion of 1 to 2.
Figure 18. Mass spectrum of compound G, expected to be 2.

Constant Current Electrolysis of 1,1-Diphenylacetone (1) and 2-Methyldiphenylmethane (17) at the Cathode. The appearance of a peak corresponding to diphenylmethane (16) during the electrolysis of 1 at the cathode under nitrogen prompted us to consider 16 as a possible intermediate in the electrochemical conversion of 1 to 2 (Scheme 8). It was postulated that the appearance of 16 under nitrogen-purged conditions could be due to the reduction of 1 to 16 as the slow step in the reaction and the oxidation of (16) to 2 as the fast step in the reaction. Under oxygenated conditions, the fast step occurs so quickly that buildup of 16 is not observed in the gas chromatograms obtained throughout the course of the reaction. However, under nitrogen-purged conditions, oxygen becomes
a limiting reagent that slows the conversion of 16 to 2 enough that the former can be observed in the gas chromatograms.

**Scheme 8.** Postulated conversion of 1 to 16 to 2 to explain the appearance of 16 during electrolyses under nitrogen.

It was decided that 2-methyldiphenylmethane (17) be used as a labeled form of 16 in order to track whether conversion of (17) to 2-methylbenzophenone occurs. If 16 were indeed an intermediate in the conversion of 1 to 2, then presumably 17 would also act as an intermediate and be converted to 2-methylbenzophenone at the cathode. The synthesis of 17 was performed following the procedure outlined by Gordon and Fry for the reduction of benzhydryl to diarylmethylene derivatives.\(^{21}\) 17 was synthesized by adding 2-methylbenzhydrol (18) to acetic acid containing iodine and 50% aqueous hypophosphorous acid, which generates hydrogen iodide *in situ* (Scheme 9).\(^{21}\) The mixture was then heated to 60°C and worked up to yield 17 in 91% yield.

**Scheme 9.** Reduction of 18 to 17 using a hypophosphorous-iodine system.
GC-MS results indicated that there was only one constituent, with a retention time of 9.740 minutes, in the product obtained from this reaction. The mass spectrum of this product gives a parent ion peak of \( m/z \) 182 and high intensity peaks of \( m/z \) 167 and 104, all of which are consistent with the structure of 17. The molecular weight of 17 is 182 g/mol. The peak of \( m/z \) 167 signifies loss of a benzylic proton and cleavage of the methyl carbon bond with the ortho aromatic carbon bond, while the peak of \( m/z \) 104 is indicative of a loss of the unsubstituted phenyl group.

**Figure 19.** Mass spectrum of 2-methyldiphenylmethane (17).
Figure 20. $^1$H NMR spectrum of 17.

A $^1$H NMR spectrum of the product shows nine protons in the aromatic region with a singlet peak at 4.03 ppm integrating for two protons. This peak corresponds to the two benzylic protons, while the singlet peak at 2.25 ppm, which integrates for three protons, coincides with the methyl protons. Based on the GC-MS and $^1$H NMR spectra, the product was pure and no further purification was performed.

The product from this synthesis was then used in the electrolysis of equimolar amounts of 17 and 1 in the cathode compartment of a divided cell. Analysis by GC-MS showed that at 60 minutes, 2-methyldiphenylmethane (17) had not been converted to anything observable in the gas chromatogram, while some of 1 had already been converted to 2. Peaks corresponding to benzhydryl acetate (14) and a
compound with a retention time of 11.49 minutes (See Section AII of the Results Section) can also be observed in the spectrum. By 180 minutes, all of 1 had been converted to 2, while it does not appear that any of 17 had converted to 2-methylbenzophenone. These results demonstrate that 17 cannot be converted to 2-methylbenzophenone at the cathode, implying that diphenylmethane (16) is not an intermediate in the formation of 2.

Figure 21. Gas chromatograms of the electrolysis of 1 and 17 at 60 minutes and 180 minutes.
What was peculiar about the GC-MS spectra obtained during this electrolysis was that the ratio of 2 that has formed is a small fraction of the amount of 17 that was left unreacted. Assuming full conversion of 1 to 2, there should be equimolar amounts of 2 and 17 in solution. Although GC-MS results are poor indicators of concentration ratios, the small amount of 2 in solution raised questions regarding whether all of 1 was being converted to 2. As a control, equal moles of 17 and commercially-available 2 were injected into the GC-MS instrument. The spectrum showed that 2 exhibited an abundance of approximately 50% of the abundance of 17. The spectrum obtained after the electrolysis, however, showed that the abundance of 2 formed was much less than 50% of the abundance of 17. Thin-layer chromatography of the product from the electrolysis shows the presence of a third spot. This may indicate that 1 is being converted to not only 2 but another product not observed in the gas chromatogram.

![Equal Mole of 2-Methylthiophene Methanes and Derivatives](image)

**Figure 22.** Equal moles of 2 and 17.
Reaction of 1,1-Diphenylacetone (1) and 2-Methyldiphenylmethane (17) with KO$_2$. The role diphenylmethane (16) plays in the conversion of 1 to 2 was checked by reacting 1 and 17 with KO$_2$. To a three-neck round bottom flask was added equal moles of 1 and 17 in dry DMF containing KO$_2$ and Et$_4$NBr. GC-MS analysis after 43 hours demonstrated that 1 had converted to 2, while most of 17 had remained stable to KO$_2$. Unlike the gas chromatogram obtained from the electrolysis of 1 and 17, the gas chromatogram obtained from reaction with KO$_2$ shows a low intensity peak with a retention time of 10.702 minutes and parent ion peak of $m/z$ 196. There are also high intensity peaks of $m/z$ 195, 182, and 105. This fragmentation pattern is consistent with the structure of 2-methylbenzophenone, which has a molecular weight of 196 g/mol. The $m/z$ 182 peak corresponds to the [M-CH$_3$]$^+$ fragment resulting from the cleavage of the methyl group in the ortho position of one of the aromatic rings, while the $m/z$ 105 peak is indicative of loss of the aromatic ring containing the methyl group. The results obtained here demonstrate that even though formation of 2-methylbenzophenone is not observed during the course of the electrolysis of 17, a small amount does form in the chemical reaction of 17 with superoxide. This suggests that diphenylmethane (16) may have the ability to react with superoxide to form 2 but probably not under the conditions used during a constant current electrolysis at 25 mA.
Figure 23. Gas chromatogram of the reaction of 1 with KO$_2$ after 43 hours and mass spectrum of the constituent postulated to be 2-methylbenzophenone.

**Constant Current Electrolysis of 1,1-Diphenylacetone (1) and Diphenylmethane (16) at the Cathode.** To see if all the diphenylmethane (16) in solution can be converted to benzophenone (2) during the course of an electrolysis, commercially-available diphenylmethane was placed in the cathode compartment with 1, and the current was turned on. The progress of the reaction was monitored by GC-MS, and the reaction was allowed to continue for six hours, running for four
additional hours after complete disappearance of 1. At 120 minutes, only 16 and 2 were observable in solution. The electrolysis was continued for four additional hours to test whether remaining 16 would convert to 2. At the end of six hours, the ratio of 16 to 2 was the same as that present at 120 minutes. These results signify that not enough of 16 is being converted to 2 in the amount of time given for 16 to be serving as an intermediate in the conversion of 1 to 2.

**Constant Current Electrolysis of 1,1-Diphenylacetone (1) with H₂¹⁸O at the Cathode.** To rule out water as a possible source of oxygen for the oxidation of 1 to 2, 1 and H₂¹⁸O were placed in dry electrolyte solvent in the cathode compartment of a divided cell and de-gassed using nitrogen for one hour. The progression of the reaction was monitored every 30 minutes using GC-MS, which showed the consumption of 1 and accumulation of 2 along with the formation of 16. The mass spectrum of 2 showed a parent peak of m/z 182 for the first 60 minutes of the electrolysis, but after 210 minutes have passed, a ¹⁸O-labeled parent peak of m/z 184 and a peak of m/z 107 indicating a benzoyl group fragment ([PhC¹⁸O]⁺) were observed (Figure 24). The presence of both peaks suggests that ¹⁸O from H₂¹⁸O was incorporated into 2, but because the initial mass spectra of 2 for the first 60 minutes did not exhibit any peak of m/z 184 or of m/z 107, it is probable that the incorporation of ¹⁸O occurred through the hydration of 2 with H₂¹⁸O and subsequent dehydration back to 2. It is, therefore, difficult to say conclusively whether water does play a role in the cleavage of the carbon-carbonyl bond of 1 to form 2.
Figure 24. Mass spectra of 2 at 60 minutes and at 210 minutes during the cathodic electrolysis of 1 in H$_2^{18}$O.

What is worth mentioning is that 16 did form during the course of the reaction. 1 had converted to 2 by 150 minutes, but the electrolysis was allowed to
continue until 210 minutes had passed, during which time the peak corresponding to 16 continued to grow until it became almost equivalent in size to the peak coinciding with 2.

B. Cathodic Cleavage of 1,1-Diphenyl Ketones

Thus far, the cleavage of the carbon-carbonyl bond of α-alkoxydiphenylacetaldehyde (6) and α-alkoxydiphenylacetone at the cathode has been observed to yield benzhydryl ethers. In all previous work, however, this cleavage has only been observed when the substituent has been an alkoxy group. If this mild, cathodic α-cleavage of diphenylacetaldehyde (3) and 1,1-diphenylacetone (1) can also occur when the α-substituent is an alkyl group, this electrochemical method will open up a variety of avenues for synthesis. Following this reasoning, it was decided that the cathodic cleavage of α-substituted 1,1-diphenyl ketones in the presence of oxygen be investigated.

Constant Current Electrolysis of 2,2,2-Triphenylacetophenone (19) at the Cathode. This constant current electrolysis of 19 was performed in 0.1M Et₄NBF₄ in acetonitrile in the cathode compartment of a divided cell. The solution was bubbled with oxygen for 30 minutes before a current of 25 mA was turned on. Samples were taken every hour and analyzed using GC-MS. The electrolysis required 250 minutes to reach completion, during which time the reaction proceeded as expected. The gas chromatograms show the peak corresponding to 19 dwindling as the product peak grows. After the product was worked up, GC-MS analysis indicated the presence of three components in the final product (Figure 25). The first peak (H) has a retention
time of 10.513 minutes, the second peak (I) has a retention time of 12.739 minutes, and the third peak (J) has a retention time of 13.602 minutes.

**Figure 25.** Gas chromatogram of the constant current electrolysis of 19 at the cathode.

Compound H has a parent peak of $m/z$ 182 and significant peaks of $m/z$ 105 and 77. The presence of these peaks and the retention time of 10.5 minutes correlate well with the GC-MS data for benzophenone (2). The appearance of this peak suggests that in the reduction of 19, 2 is also formed.
Figure 26. Mass spectra of a) compound H, thought to be benzophenone (2); b) compound I, postulated to be triphenylmethane (20); and c) compound J, which is believed to be triphenylmethanol (21).
As the major constituent of the product, compound I has a parent peak of \( m/z \) 244, the molecular weight of triphenylmethane (20). The peak of \( m/z \) 167 corresponds to the \([M-\text{Ph}]^+\) fragment and the peak of \( m/z \) 165 corresponds to a loss of two additional protons from the \( m/z \) 167 fragment. This fragmentation pattern is consistent with the structure of 20. Compound J has a parent peak of \( m/z \) 260 and high intensity peak of \( m/z \) 183, both of which suggest that J is triphenylmethanol (21). 21 has a molecular weight of 260 g/mol, and a peak of \( m/z \) 183 signifies loss of a phenyl group from the molecular ion. Comparison of its fragmentation pattern to that reported in the literature helped to confirm that compound J is 21.22

A \(^1\)H NMR taken of the product from the reduction of 19 exhibits multiple peaks in the aromatic region (Figure 27). The presence of numerous peaks in this area made assignment difficult, but the presence of a singlet peak at 5.59 ppm agrees well with what is reported in literature.23 This peak is expected to be the benzylic proton, which signifies that 19 was cleaved at the cathode to 20. The two peaks between 2.8 ppm and 3.0 ppm correspond to DMF leftover in the product. It is often observed that when electrolyses are carried out for a long period of time, some of the conducting gel used to separate the anode and cathode begins to dissolve, causing DMF to leak into the cathode compartment. Mass and \(^1\)H NMR spectral data suggest that 20 was formed at the cathode during the electrolysis of 19.
Figure 27. $^1$H NMR spectrum of the product from the reduction of 2,2,2-triphenylacetophenone. It is postulated that the product is 20.

**Constant Current Electrolysis of 1-Methyl-1,1-Diphenylacetone (22) at the Cathode.** Before the electrolysis of 22 could be carried out, 22 had to be synthesized using the protocol developed by Salama, et al. Acetophenone was placed in DCM containing tetrachlorosilane-zinc in a 1:4:6 ratio. The mixture was quenched, filtered, and then extracted using DCM. The solvent was removed in vacuo, and the product was purified using column chromatography (50:50 hexanes:DCM). GC-MS analysis of the final product showed only one constituent with a mass spectrum containing a parent peak of m/z 224, which is the molecular weight of 22. The peak of m/z 181 corresponds to α-cleavage and loss of the acyl group, while the peak of m/z 165 represents the fragment formed with loss of the acyl
and methyl groups and a hydrogen. This fragmentation pattern is consistent with the structure of 22 (Figure 28).

Figure 28. Mass spectrum and $^1$H NMR spectrum of 22.
Moreover, a $^1$H NMR spectrum shows a singlet at 1.89 ppm that integrates for three protons, which corresponds to the protons on the methyl group attached to the benzylic carbon, a singlet at 2.17 ppm that integrates for three protons, which is representative of the $\alpha$-protons on the ketone, and a multiplet that falls within the aromatic region and integrates for ten protons (Figure 28). Based on this spectrum, it was concluded that 22 was generated and purified, and it was used in subsequent cathodic reactions.

The constant current electrolysis of 22 was performed in the cathode compartment of a divided cell, which was purged with oxygen prior to turning on the current. During the course of the reaction, the current started fluctuating and dropped as low as 8 mA due to the high voltage required for the reaction to occur. As a result, the electrolysis was paused and restarted multiple times over two days. The progress of the reaction was monitored using GC-MS, and the gas chromatograms obtained at 60 minutes, 180 minutes, and 600 minutes are shown in Figure 29. The reaction took 600 minutes to reach completion, leaving one major constituent, with a retention time of 9.452 minutes, in solution. The mass spectrum of this compound has a parent peak of $m/z$ 182, which is the molecular weight of 1,1-diphenylethane (23). The high intensity fragment of $m/z$ 167 indicates loss of the methyl group from the structure of 23.
Figure 29. Gas chromatograms following the progression of 22 to 23.
\(^1\)H NMR analysis of the product obtained from the electrolysis of 22 indicates that there is a doublet peak at 1.62 ppm that integrates for three protons and a quartet peak at 4.18 ppm that integrates for one proton. The doublet is most probably the methyl protons which are split by the single benzhydryl proton. The quartet peak demonstrates that the benzhydryl proton is present and, ultimately, that the carbon-carbonyl bond of 22 was cleaved. The peaks in the aromatic region of the spectrum also integrate for ten protons, which is consistent with the structure for 23. The remaining peaks present in the spectrum include a small peak at around 8.02 ppm and a pair of peaks around 2.97 ppm that are the residual DMF solvent peaks.

![Figure 30](image)

**Figure 30.** \(^1\)H NMR spectrum of the product from the reduction of 22.

**Constant Current Electrolysis of 6,6-Diphenyl-5-Decanone (24) at the Cathode.** 24 was synthesized prior to carrying out the electrolysis by following the same procedure used in the synthesis of 22.\(^{24}\) Valerophenone was added to a three-neck round bottom flask containing SiCl\(_4\) and zinc dust stirring in DCM. The solution
was worked up after 20 hours, and the product was purified using column chromatography (50:50 hexanes:DCM). A GC-MS spectrum (Figure 31) taken of the final product showed one major component with a retention time of 13.727 minutes and a parent peak of $m/z$ 279, which corresponds to the $[\text{M-} \text{C}_2\text{H}_5]^+$ fragment. It is probable that the low abundance of the molecular ion prevented it from showing up in the mass spectrum. The other high intensity fragments, including peaks of $m/z$ 223 and 167, serve to bolster the conclusion that 24 had been synthesized. A peak of $m/z$ 223 is representative of the loss of the acyl group, while the peak of $m/z$ 167 corresponds to the loss of both the acyl and butyl groups. The $^1$H NMR spectrum (Figure 31) contains a multiplet at 0.64-1.40 ppm that integrates for 14 hydrogens and another multiplet at 2.26 ppm that integrates for four hydrogens, accounting for the 18 hydrogens of the ketone and butyl group. The remaining ten protons are also all accounted for in the aromatic region.
Figure 31. Mass spectrum and \textsuperscript{1}H NMR spectrum of 24.

The constant current electrolysis of 24 was carried out in a similar fashion to the electrolysis of 22, but difficulties concerning the fluctuating current arose. 24 was placed in the cathode compartment of a divided cell, and the solution was purged with
air for 30 minutes prior to turning on the current. The progress of the reaction was monitored periodically by GC-MS, but the current kept fluctuating, possibly due to high adsorption, so the reaction was stopped after 28 hours. The gas chromatogram at the end of 28 hours (Figure 32) shows three major peaks, one with a retention time of 11.183 minutes (K), one with a retention time of 12.133 minutes (L), and one with a retention time of 13.770 minutes (M).

![Gas chromatogram of the reduction of 24 after 28 hours.](image)

**Figure 32.** Gas chromatogram of the reduction of 24 after 28 hours.

Compound K has a parent peak of $m/z$ 224 and is predicted to be 1,1-diphenylpentane (25), which has a molecular weight of 224 g/mol. The high intensity peak of $m/z$ 167 corresponds to loss of the butyl group (Figure 33).
**Figure 33:** Mass spectra of a) compound K, which is expected to be 25; b) compound L, a possible intermediate; and c) compound M, the starting ketone.
Compound L has a parent peak of \( m/z \) 222 and high intensity peaks of \( m/z \) 193, 183, and 105. The \( m/z \) 183 and 105 peaks are indicative of the presence of oxygen, possibly bonded to the benzylic carbon. Although L cannot be identified without having isolated it, its mass spectrum suggests that it could be an intermediate containing a hydroperoxy group. Compound M has a fragmentation pattern that coincides with what was seen for 24. These GC-MS results indicate that although the reaction had not reached completion, the expected product from \( \alpha \)-cleavage of \( \alpha \)-substituted 1,1-diphenyl ketones was forming.

C. Mechanistic Studies of the Cathodic Cleavage of 1-Methyl-1,1-Diphenylacetone (Representative Case)

The experiments detailed in this section were carried out to study the mechanism for the cleavage of \( \alpha \)-substituted 1,1-diphenyl ketones by using 1-methyl-1,1-diphenylacetone (22) as the representative case. The role oxygen and superoxide play in this cleavage and the nature of the intermediate formed were investigated.

I. Electrolyses

To investigate whether the cathodic cleavage of 1,1-diphenyl ketones proceeds via a carbanion or radical intermediate, mechanistic studies were performed on 1-methyl-1,1-diphenylacetone (22) as a representative compound for other 1,1-diphenyl ketones. Deuterium ion and atom donors were added to solutions to be electrolyzed, and GC-MS was used to determine if incorporation of deuterium occurred. Incorporation of deuterium when a deuterium ion donor is added signals a
carbanion pathway, while incorporation of deuterium when a deuterium atom donor is added implies a radical pathway.

**Constant Current Electrolysis of 1-Methyl-1,1-Diphenylacetone (22) in the Presence of D₂O.** Using D₂O as a deuterium ion donor, a constant current electrolysis was attempted by placing 22 in the cathode compartment of a divided cell containing 200 mM D₂O in electrolyte solvent, but difficulties arose that prevented the reaction from running at a constant 25 mA. As the reaction proceeded, the current began to drop from 25 mA to 0 mA, signaling an increasing resistance. Despite changing out the carbon cloth and synthesizing a new conducting gel, the same drop in current occurred again as had been happening with α-substituted 1,1-diphenyl ketones examined in this thesis. This may be due to the compound’s tendency for high adsorption. Fortunately, the reaction proceeded just long enough for viable mass spectroscopic data to be obtained. The GC spectrum in Figure 34 shows the presence of two peaks after 12 hours. The peak with a retention time of 9.453 minutes has a parent ion peak of m/z 182, which corresponds to the molecular weight of the expected 1,1-diphenylethane (23) product (Figure 34). The high intensity peak of m/z 167 corresponds to the loss of a methyl group. The retention time and fragmentation pattern matches that discussed on Page 56. The fragmentation pattern exhibited by the peak at a retention time of 11.365 minutes parallels that of 22, indicating that this peak is unreacted starting material. What is worth noting is that there does not seem to be any incorporation of deuterium in the mass spectrum of 23. The small m/z 183 peak is of the same abundance as the m/z 183 peak in the mass spectrum of 22 produced in the absence of any deuterium ion or atom donors. The presence of a m/z
183 peak at all may be due to the natural abundance of deuterium. These results seem to suggest that the cleavage of 1,1-diphenyl ketones does not proceed via a carbanion pathway.

**Figure 34.** Gas chromatogram of the reduction of 22 in D₂O and mass spectrum of 23.

**Constant Current Electrolysis of 1-Methyl-1,1-Diphenylacetone (22) in the Presence of CH₃CDOHCH₃.** A procedure outlined by La Perriere et al. and
Pritts and Peters was utilized in the preparation of 2-deuterio-propanol (26).\textsuperscript{25} 26 was synthesized by adding spectral-grade acetone to lithium aluminum deuteride in dry diethyl ether placed in an ice bath. The reaction was left to stir overnight, quenched with water, and distilled to yield the final product. A $^1$H NMR spectrum, shown in Figure 35, of the product exhibited no methine signal, which is indicative of replacement of the methine proton with deuterium. The peak at 1.18 ppm integrates for six protons and corresponds to the six terminal protons on either side of 26. The proton on the alcohol group is accounted for by the peak at 1.70 ppm, and the other peaks correspond to residual diethyl ether solvent.

**Figure 35.** $^1$H NMR spectrum of 2-deuterio-propanol (26).

Using 26 as a deuterium atom donor, another constant current electrolysis was attempted with the same results as the electrolysis in D$_2$O. The current began to drop
during the course of the reaction, and the carbon cloth and conducting gel were replaced to force the reaction to continue long enough for mass spectroscopic data to be obtained. After 14 hours, the gas chromatogram shows a small peak with a retention time of 9.484 minutes and parent peak of $m/z$ 182, which was identified as 23 following the same reasoning as described above (Figure 36). The peak with a retention time of 11.377 minutes was characterized as starting material 22. Once again, there does not appear to be any incorporation of the deuterium atom based on the results of the mass spectrum of 23 (Figure 36). Because the results are inconclusive, another experiment may have to be developed to determine whether the mechanism for the cathodic cleavage of ketones involves a carbanion or radical pathway.
II. Reaction with Chemically-Generated Superoxide

Reaction of 1-Methyl-1,1-Diphenylacetone (22) with KO₂. The reduction of 22 was also performed using authentic superoxide, with the reaction taking two weeks to reach completion. Based on the GC-MS taken at the end of the two weeks (Figure 37), the major product of the reaction was identified to be 23 using the same reasoning as described above. The peak with a retention time of 9.646 minutes and a parent ion peak of m/z 180 was not isolated and could not be isolated. The peak with a
retention time of 10.496 minutes and a parent ion peak of $m/z$ 198 is worth noting because it has significant peaks of $m/z$ 183 and 105, usually indicative of a carbon-oxygen bond. An alkyl peroxy intermediate, such as one containing both phenyl groups bonded to a benzylic carbon that is also bonded to a peroxy group, is expected to have a molecular weight of 198 g/mol. It is possible that this peak corresponds to this intermediate or byproduct.

Figure 37. Gas chromatogram of the reaction of 22 with KO$_2$ after two weeks.
Figure 38. Gas chromatogram of the reaction of 22 with KO₂ after 20 hours.

The long reaction time for 22, especially in comparison to the 20 hours it took for 1,1-diphenylacetone (1) to react completely, is also noteworthy. A gas chromatogram obtained after the first 20 hours show that only approximately 20% of the starting material had converted to product (Figure 38). The inherently slow reaction time for (22) suggests that its α-cleavage may occur at a much slower rate than cleavage of 1.
Discussion

A. Mechanism for the Cathodic Conversion of 1,1-Diphenylacetone to Benzophenone

Based on the results obtained from the constant current electrolysis of 1,1-diphenylacetone (1) in the presence of 2-phenylethanol at the anode, conversion of 1 to benzhydryl phenethyl ether (11) is an oxidative process. 1 undergoes α-cleavage once an electron is removed from the carbonyl oxygen and forms a radical species and an acyl cation. The radical species may then be oxidized again to give a cation that is attacked by 2-phenylethanol in solution, yielding the final 11 (Scheme 4). This postulated two-electron oxidation differs from the conversion of 3 to the benzhydryl ethers (7), which proceeds via the enol tautomer of 3 (3a). Sheludko and Baum’s findings indicate that the mechanism for the latter process requires participation from both electrodes. It is hypothesized that the first step of the anodic process involves removal of a π-bonding electron from 3a to give a radical cation that is attacked by a nucleophile in solution to yield a radical species. Further oxidation and addition of a nucleophile is thought to give a hemiacetal that decomposes to the α-alkoxyaldehyde (6). From this point on, it is thought that 6 migrates to the cathode, where it is transformed to the 7.

The observed conversion of 1,1-diphenylacetone (1) to benzophenone (2) at the cathode suggests that oxygen may be the species that is being reduced to superoxide in order to facilitate formation of an α-hydroperoxy ketone intermediate. The latter is then expected to decompose to 2. The capability of 1 to form a hydroperoxy intermediate in the presence of superoxide may account for the cathodic
cleavage of 6 to 7. In order to confirm whether oxygen is a primary reagent in the abovementioned cathodic cleavage, the role oxygen plays in the conversion of 1 to 2 was studied.

Based on the data gathered from the attempted autoxidation of 1, 1 does not react with molecular oxygen in air in a mechanism similar to the aerobic oxidation of diphenylacetaldehyde (3). It is likely that the reason behind this stability in air is that oxidation would proceed via the enol, which Boris Sheludko had shown is only minimally involved in the oxidation of 1. In fact, ketones contain, on average, 10-1000 times less enol content than their corresponding aldehydes. The observed conversion of 1 to 2, therefore, does not occur aerobically but primarily through electrochemical means. The cathodic conversion of 1 to 2 in a divided cell was investigated through various experiments, and the data presented in the Results section provide evidence supporting the proposed mechanism in Scheme 10.

Scheme 10. Proposed mechanistic pathway for the conversion of 1 to 2 at the cathode.
We believe the conversion of 1 to 2 at the cathode probably occurs with the one-electron reduction of molecular oxygen to superoxide, a dioxygen species that is quite ubiquitous in nature.\textsuperscript{13b} Superoxide, an anion with one unpaired electron, would go on to abstract the benzylic hydrogen from 1, leaving a radical intermediate that reacts again with another molecule of superoxide to afford an \( \alpha \)-hydroperoxy ketone intermediate. The carbonyl undergoes nucleophilic attack by a hydroperoxy anion (HOO\(^{-}\)), which is known to be a powerful nucleophile, to give a tetrahedral intermediate which decomposes to 2.\textsuperscript{27}

The rationalization for this proposed mechanism is grounded in what Kaimakliotis and Fry have found regarding the cathodic cleavage of the carbon-silicon bond of \( \alpha \)-dimethylsilyl esters in the presence of electrochemically-generated superoxide.\textsuperscript{14} Addition of superoxide to the silicon atom of the ester facilitates cleavage of the carbon-silicon bond. Presumably, addition of superoxide can also cleave a carbon-carbon bond. Singh and Singh have also reported that reaction of superoxide with benzhydryl substrates proceeds first through hydrogen atom abstraction.\textsuperscript{28} After this initial step, a molecule of molecular oxygen reacts with the radical species generated, and addition of a proton results in formation of an alkyl hydroperoxide by a well-known autoxidation process (R-H to ROOH).\textsuperscript{29} It was postulated by Singh and Singh that subsequent abstraction of a second hydrogen from what results in a radical species that loses a hydroxyl radical to form a ketone. It is therefore reasonable to suggest that the first step in the conversion of 1 to 2 involves the abstraction of the benzylic hydrogen atom to form a radical intermediate that reacts with another molecule of superoxide to form an \( \alpha \)-hydroperoxy ketone. The
remarkable nucleophilicity of superoxide also facilitates addition to the carbonyl to form a tetrahedral intermediate that breaks apart to 2.²⁷

Scheme 11. Reaction of superoxide with benzhydryl substrates, as reported by Singh and Singh.²⁸

The series of experiments reported herein indicates that the reduction of oxygen at the cathode is responsible for the conversion of 1 to 2. Constant current electrolysis of 1 at the cathode in the presence of oxygen proceeds to 2 at a faster rate than the electrolysis in the absence of oxygen. As mentioned earlier, the structure of the divided cell allows oxygen from air to diffuse into the electrolyte solvent, facilitating conversion of 1 to 2 because oxygen is still available to be reduced even after flushing with nitrogen. As a result, 2 still forms even when the reaction is carried out under nitrogen. However, purging the solution with nitrogen before and during the electrolysis removes a large enough amount of oxygen to slow the conversion of 1 to 2 by approximately 32%, if not more, compared to the reaction carried out under oxygenated conditions.
In addition, both experiments show a small peak that is present in all gas chromatograms of the electrochemical conversion of 1 to 2. The mass spectrum of this compound has a parent peak of \( m/z \) 210 and high intensity peaks of \( m/z \) 183, 167, and 105, all of which suggest that this compound may be an intermediate containing oxygen bonded to the \( \alpha \)-carbon. It is possible that this intermediate is \( \alpha \)-hydroperoxydiphenylacetone, whose parent peak of \( m/z \) 242 is not observable in the mass spectrum. This would not be surprising since even diphenylacetone (1) produces a very small, low-intensity parent ion.

The reaction of 1 with pre-electrolyzed oxygen demonstrates the effect reducing oxygen has on the transformation of 1 to 2. Reducing oxygen in dry electrolyte solvent and placing 1 into the compartment after turning off the current shows almost immediate conversion of 1 to 2. Because 1 is stable in air, the conversion observed here must be due to a chemical, rather than electrochemical, reaction with the product formed from the reduction of oxygen, which we postulate to be superoxide. Moreover, despite stirring 1 for 40 hours, only a relatively small amount of 2 was formed, suggesting that it is possible that the dioxygen species generated \textit{in situ} is unstable for longer periods of time.

Most crucial to understanding the reduction of oxygen are the results obtained from the cyclic voltammetry experiments. It is shown that under nitrogen-purged conditions, no reduction peak is observed, but under oxygenated condition, a large reduction peak that corresponds to the reduction of molecular oxygen is observed. Of particular interest, however, is that when 1 is placed in the voltammetric cell in the presence of oxygen, another reduction curve is observed that is completely absent.
when the solution is bubbled with nitrogen prior to turning on the current. Because benzophenone (2) is expected to exhibit a reduction curve that begins at -2.0V, a cyclic voltammogram of an authentic sample of 2 dissolved in electrolyte solvent was obtained and compared to the cyclic voltammogram of 1 in the presence of oxygen. The reduction of 2 coincides with the reduction peak observed in the cyclic voltammogram of 1 under oxygen, confirming that 2 is being formed when oxygen is present but not when nitrogen is present. These results suggest that 1 is reacting with a dioxygen species, such as superoxide, formed from the reduction of molecular oxygen to generate 2, which is then observed to be reduced at -2.3V.

The key experiment that confirms that superoxide is the dioxygen species that is reacting with 1 to form 2 at the cathode is the reaction of 1 with KO₂. The successful generation of 2 in a solution containing 1 and authentic superoxide demonstrates that superoxide, including electrochemically-generated superoxide, is capable of converting 1 to 2. It is worth noting, however, that even though superoxide is the most likely reagent in this reaction, results from the reaction of 1 in Na₂O₂ also indicate that peroxide has the capability of oxidizing 1 to 2. The conversion of 1 to 2 in the presence of peroxide did require a much longer period of time than in the presence of superoxide, suggesting that the rapid but mild, cathodic conversion of 1 to 2 probably involves superoxide. It cannot be ruled out, however, that a small fraction of 2 could be formed via varying mechanistic pathways that involve more than one dioxygen species, including but not limited to hydroperoxyl radical, peroxide anion, and hydrogen peroxide.
Further mechanistic studies were performed to answer the question of why benzhydryl acetate (14) and diphenylmethane (16) are products in the cathodic conversion of 1 to 2 and what further reactions they are involved in. It is postulated that if superoxide is forming in situ as molecular oxygen is reduced at the cathode, superoxide could also interact with 1 via nucleophilic attack at the carbonyl first to form a tetrahedral intermediate. The benzhydryl group would migrate to the oxygen of the peroxy group in a Baeyer-Villiger rearrangement to afford 14 (Scheme 12). The possibility for this mechanism suggests that superoxide can attack the carbonyl first or initiate homolytic cleavage of the α-carbon and hydrogen bond.

Scheme 12. Proposed mechanism for the formation of 14.

Because 14 often appears in the gas chromatograms taken of the conversion of 1 to 2 at the cathode, 14 was placed in the cathode of a divided cell, and results indicate the formation of both 16 and 2. The generation of both compounds from 14 suggests that 14 may be an intermediate in the conversion of 1 to 2. It is also possible that 14 is simply a product from another mechanistic pathway that proceeds in the reaction as a minor contributor to the formation of 2 and 16. It is postulated that a likely mechanism for the conversion of 14 to 2 resembles the pathway for the conversion of 1 to 2, with superoxide abstracting the benzylic hydrogen as another
molecule of superoxide reacts with the radical species to form an α-hydroperoxy ester intermediate (Scheme 13). The carbonyl is attacked by a hydroperoxyl anion, leading to formation of a tetrahedral intermediate that decomposes to form 2.

Scheme 13. Postulated mechanism for the conversion of 14 to 2.

The reduction of 14 results in 16 as the major product. A possible rationalization for this conversion is presented in Scheme 14. 14 can undergo single-bond electrolytic cleavage. Although carbon-oxygen bonds are generally stronger than carbon-halogen bonds of alkyl halides, single-bond electrolytic cleavage can still occur, especially when the carbon-oxygen bond is alpha to a carbonyl group. The carbon-oxygen bond being cleaved in the case of 14 is indeed alpha to the carbonyl group, and the radical species formed after the bond has been homolytically cleaved is stabilized by the presence of both phenyl groups. The large conjugated π-system provided by the phenyl groups further stabilizes the radical intermediate formed in the reduction of 14. Moreover, electron transfer to the benzhydryl radical should be facile.
because the electron would be added to a nonbonding orbital. Addition of another electron gives the benzhydryl anion that is then protonated to form 16.

Scheme 14. Proposed mechanism for the conversion of 14 to 16.

16 was observed to have formed in the constant current electrolyses of 1 at the cathode under nitrogen-purged conditions. Under oxygenated conditions, however, no formation of 16 was observed. It was first postulated that formation of 16 could be the slow step in the conversion of 1 to 2, and oxidation of 16 to 2 could be a fast step in the reaction. Under oxygen, enough superoxide could form that buildup of 16 is never observed, but under nitrogen, the availability of oxygen would be so limited that conversion of 16 to 2 can be observed in the gas chromatograms. However, results from the constant current electrolyses of 2-methyldiphenylmethane (17) at the cathode indicate that, at a current of 25 mA and in the time allowed for a typical electrolysis to run, conversion of 17 to 2-methylbenzophenone was not observed.
Even an electrolysis of authentic 16 did not show conversion to 2. This implies that it would be very unlikely that 16 is an intermediate in the conversion of 1 to 2. However, it is worth noting that when 17 was stirred with KO₂ for 43 hours, a small amount of 2-methylbenzophenone was observed, suggest that under harsher conditions, the conversion of 16 to 2 can occur but probably not under the conditions electrolyses are usually carried out.

B. Mechanism for the Cathodic Cleavage of α-Substituted 1,1-Diphenyl Ketones

**Mechanism Determination.** The data from the constant current electrolyses of α-substituted 1,1-diphenyl ketones at the cathode show that cleavage of the carbon-carbonyl bond occurs through a pathway comparable to that through which 1 is converted to 2 (Scheme 15). The results from the reaction of 1-methyl-1,1-diphenylacetone (22) with KO₂ confirmed that superoxide is also involved in α-cleavage of α-substituted 1,1-diphenyl ketones. We propose that oxygen is first reduced to superoxide, which then abstracts a hydrogen to form a hydroperoxy anion. The carbonyl is then attacked by this anion to give a tetrahedral intermediate. As the intermediate collapses to reform the carbonyl, the carbon-carbonyl bond gets cleaved. Deuterium-labeling studies were performed to investigate whether the intermediate that forms after the α-cleavage step is a radical or carbanion, but the results were inconclusive. According to the GC-MS spectra obtained, neither a deuterium atom or ion was observed to have been incorporated into the final 1,1-diphenylethane product. However, the most likely mechanism would require a carbanion intermediate that is
then protonated to give the final product. It could be that the hydroperoxy anion itself is the proton donor, generating peroxide in the process.

**Scheme 15.** Proposed mechanistic pathway for the cleavage of α-substituted 1,1-diphenyl ketones.

**Difficulties.** During the constant current electrolyses of the α-substituted 1,1-diphenyl ketones discussed in this thesis, a common problem that was experienced throughout each experiment was the high voltage that was required for each reaction. This caused the current to fluctuate, often decreasing to 10 to 0 mA, which ultimately required the electrolyses to be stopped. It was thought that the dropping current could be due to an increasing resistance in solution, possibly caused by adsorption to the carbon cloth electrodes or to the methylcellulose conducting gel. In an attempt to solve this problem, the electrolyses were often stopped, the carbon cloths were changed, and a new conducting gel was prepared. These efforts would often work for a short time, which may be enough for the reaction to reach completion, but in some cases, such as the deuterium-labeling experiments and the electrolysis of 6,6-diphenyl-5-decanone (24), the reactions could not be continued.
C. Applications and Future Directions

It was discussed in previous sections that the mechanism for the conversion of 1,1-diphenylacetone (1) to benzophenone (2) was studied in order to shed more light on the cathodic conversion of α-alkoxyacetaldehyde (6) to benzhydryl alkyl ether (7). Results from the experiments reported here demonstrate that molecular oxygen is reduced to superoxide, or a variety of other dioxygen species, which migrates to 1 and initiates a multi-step reaction that ultimately oxidizes 1 to 2. This cathodic transformation involves breaking of a carbon-carbonyl bond—the same bond that is broken in the generation of benzhydryl ether from α-alkoxyacetaldehyde. Superoxide, generated in situ, has also been shown to be responsible for α-cleavage of substituted 1,1-diphenyl ketones. The results gathered here suggest that, analogously, reduction of oxygen at the cathode to superoxide and subsequent reaction with the substrate afford the cleavage and decarbonylation of α-alkoxyacetaldehyde to benzhydryl ether. Consequently, the conversion of diphenylacetaldehyde (3) to benzhydryl ether in the presence of alcohols occurs via anodic oxidation of 3 to α-alkoxyacetaldehyde, which then migrates to the cathode where it reacts with superoxide generated in situ to afford benzhydryl ether. This would only be the second example of a paired electrosynthesis that involves significant structural transformation at the anode and, subsequently, at the cathode to afford a new synthetic product.  

Though progress has been made in understanding the cleavage of α-substituted 1,1-diphenyl ketones, much still remains to be elucidated. As a result of difficulties that arose in the electrolysces of α-substituted 1,1-diphenyl ketones, it could not be determined whether the conversion of the ketones studied to their
corresponding alkanes proceeds via a carbanion or radical intermediate. In addition, future research includes carrying out the cathodic cleavage of 1,1-diphenyl ketones by employing a variety of different α-substituted ketones. Substituents should include more sterically-hindered alkyl groups, alkenes, and alkoxy groups in order to explore the synthetic capacity of this unusually mild cathodic cleavage of carbon-carbonyl bonds.
Experimental

A. General

Instrumentation and Materials. Gas chromatography-mass spectrometry (GC-MS) data were acquired using an Agilent Technologies 6890 Network GC system with a 5797 Network mass selective detector. Two GC oven methods were used—the majority of GC-MS acquisitions used Method 1 and the reduction of 6,6-diphenyl-5-decanone (24) used Method 2. Method 1 required the initial oven temperature to start at 50°C, where it was held for three minutes, after which time the temperature increased at 17°C/min to a final temperature of 250°C, where it was held for another three minutes. This method resulted in a total run time of 17.76 minutes. Method 2 consisted of an initial oven temperature of 50°C, where it was held for three minutes, after which time the temperature was ramped at 17°C/min to a final temperature of 250°C, where it was held for an additional ten minutes, resulting in a total run time of 24.76 minutes. The final temperature is held longer in Method 2 to ensure the removal of any high boiling materials from the GC column. A 2.5 minute solvent delay was employed in all cases.

All NMR spectra were obtained at Wesleyan University on either the Varian Mercury 300 MHz or Varian Unity Plus 400 MHz NMR spectrometer. Which instrument was used to obtain each spectrum is noted in the results. All chemical shifts are given relative to an internal TMS standard.

Cyclic voltammetry experiments were performed on a CHI650A (Austin, TX, USA) computer system. All experiments were carried out in a 10 mL solution of 0.1 M tetraethylammonium tetrafluoroborate in acetonitrile at a scan rate of 0.1 V/s. A
silver wire in 0.1 M silver nitrate acetonitrile solution was used as the reference electrode, and glassy carbon and a platinum wire were used as the cathode and anode, respectively (Figure 38).

Unless otherwise noted, all reagents were purchased from commercial sources.

![Voltammetric cell set-up for cyclic voltammetry experiments.](image)

**Figure 38.** Voltammetric cell set-up for cyclic voltammetry experiments.

**Typical Constant Current Divided-Cell Electrolysis.** Divided-cell electrolyses were carried out in a glass reaction vessel (Figure 39) containing a magnetic stir bar and a counter and working electrode, each consisting of a 2 cm by 2 cm carbon cloth threaded through a platinum wire. The cathode and anode compartments were separated by a conducting gel prepared using methylcellulose-saturated DMF containing 0.1 M tetraethylammonium tetrafluoroborate dripped onto a fritted disk membrane separating the two chambers of the divided cell. The gel was allowed to cool and harden around the electrode. All electrolyses used 75 mL of 0.1 M tetraethylammonium tetrafluoroborate, unless otherwise noted, in dry acetonitrile as the electrolyte solution. Stock solutions were prepared beforehand and stored over molecular sieves (3A, 8-12 mesh, 10% m/v) for at least 24 hours to ensure
minimal water content. All constant current electrolyses were carried out at 25 mA. The reaction vessel was stoppered with rubber septa, through which the platinum wires and gas needle were threaded. Prior to each reaction, nitrogen gas or atmospheric oxygen was bubbled through the solution for 20 to 30 minutes and for the remainder of the reaction. When a reaction had to be paused overnight, the solution was degassed again for 20 to 30 minutes prior to turning on the current. Nitrogen gas was used in the experiments that necessitated an oxygen-free environment, and atmospheric oxygen was utilized to afford the cathodic cleavage of the 1,1-diphenyl ketones. The progress of each reaction was monitored by working up the reaction mixture and injecting the organic phase into the GC-MS instrument for analysis. A standard mini-workup involved withdrawing 0.1 mL of the reaction mixture and adding 0.5 mL of deionized water and 0.5 mL of hexanes to the sample in a test tube. The mixture was then agitated, and the top organic layer was siphoned off to be injected into the GC-MS instrument.

A standard workup procedure for all electrochemical reactions consisted of removing the electrolyte solution in vacuo. The yellow-brown oil remaining contains both the product and the electrolyte salt, tetraethylammonium tetrafluoroborate. This oil was then dissolved in approximately 50 mL deionized water and extracted three times with 15 mL diethyl ether. The organic layers were combined and dried over sodium sulfate before the solvent was removed in vacuo to yield the crude product. Further purification was performed as necessary.
**Figure 39.** A typical setup for constant current divided-cell electrolyses.

**B. Syntheses**

This section includes, in detail, the syntheses performed this semester. The compounds are listed in numerical order.

**Benzhydryl Acetate (14).** To identify the \( m/z \) 226 peak on the GC-MS spectra in the constant current electrolys of 1,1-diphenylacetone (1) at the cathode, 14 was synthesized. To a test tube placed in a cold water bath was added 0.90 mL (9.5x10\(^{-3}\) mol) acetic anhydride, 1.6155 g (8.769x10\(^{-3}\) mol) benzhydrol, and one drop of concentrated sulfuric acid.\(^{17}\) The test tube was then placed in an oil bath at
approximately 70°C for 38 minutes before it was taken off the heat. Eight drops of deionized water were added, and the mixture was agitated. Another 6 mL of half-saturated NaCl solution were added and mixed thoroughly. The water layer was removed before the ester layer was washed two more times with 6 mL of saturated NaCl solution. The ester layer was transferred to another test tube where it was dried using a small amount of Na₂SO₄ and then injected into the GC-MS instrument for analysis. % yield = 57%; GC: rt = 11.027 min (14); MS: m/z (14) 226 ([M]⁺), 184, 166, 165. ¹H NMR (400 MHz, CDCl₃): δ 2.17 (s, 3H), 6.90 (s, 1H), 7.25-7.40 (m, 10H).

Methyl Diphenylacetate (15). In order to prove definitively that the peak m/z 226 is not 15 but 14, 15 was synthesized and the mass spectrum was compared to that of 14. To a 50-mL round bottom flask equipped with a condenser and stir bar was added an excess of methanol (12.0 mL; 2.96x10⁻¹ mol), 7.9804 g (3.7601x10⁻² mol) diphenylacetic acid, and 0.3555 g (about 10 mol %) concentrated sulfuric acid.³² The mixture was refluxed overnight and allowed to cool to room temperature before a sample was taken to be analyzed by GC-MS. The mass spectrum indicated that the peak m/z 226 appearing in the electrolyses of 1 to 2 does not correspond to the mass
spectrum of 15. No isolated yield was obtained. GC: rt = 11.284 min (15); MS: m/z 226 ([M]⁺), 167, 165, 152.

2-Methyldiphenylmethane (17). This compound was synthesized to test whether there was another pathway, through diphenylmethane (16) as an intermediate, in the conversion of 1,1-diphenylacetone (1) to benzophenone (2). To a 100 mL three-neck round bottom flask equipped with a stir bar, condenser, drying tube, and nitrogen line was added 30 mL of acetic acid, 0.7960 g (4.015x10⁻³ mol) 2-methylbenzhydrol, 1.0100 g (3.9794x10⁻³ mol) iodine beads, and approximately 2 mL of 50% aqueous hypophosphorous acid.²¹ The reaction mixture was stirred at 60°C for 24 hours, diluted with water, and extracted with hexanes. The organic layer was dried over Na₂SO₄ and the solvent was removed in vacuo to yield 0.6623 g of a yellow oil. Analysis by GC-MS and ¹H NMR showed only a single constituent, and no further purification was required. % yield = 91%; GC: rt = 9.759 min (17); MS: m/z (17) 182 ([M]⁺), 167, 152, 104, 89; ¹H NMR (300 MHz, CDCl₃): δ 2.25 (s, 3H), 4.03 (s, 2H), 7.10-7.38 (m, 9H).
1-Methyl-1,1-Diphenylacetone (22). This compound was synthesized as a starting substrate for further analysis of the cathodic cleavage of 1,1-diphenyl ketones. This procedure is representative of all future attempts to synthesize this starting material and requires acetophenone, silicon tetrachloride, and zinc in a 1:4:6 ratio. To a 100 mL three-neck round bottom flask equipped with a stir bar, condenser, and drying tube was added 40 mL CH₂Cl₂, 6.9862 g (1.0684x10⁻¹ mol) zinc dust, and 2.1723 g (1.8080x10⁻² mol) acetophenone. The reaction mixture was allowed to stir for five minutes at room temperature before 8.20 mL (7.16x10⁻² mol) silicon tetrachloride was added dropwise. The reaction was left to stir at room temperature for 20 hours until GC-MS showed complete disappearance of the starting material. The reaction was then poured onto water and filtered, and the filtrate was extracted with CH₂Cl₂. The extracts were dried over Na₂SO₄, and the solvent was removed in vacuo to yield 0.9776 g of a gray-pink liquid in 48% crude yield. This crude material was purified via column chromatography (50:50 hexanes:dichloromethane) to give 0.7860 g of a yellow oil. % yield = 39%; GC: rt = 11.352 min; MS: m/z 224 ([M⁺⁺), 181, 165, 103, 77; ¹H NMR (300 MHz, CDCl₃): δ 1.89 (s, 3H), 2.17 (s, 3H), 7.18-7.40 (m, 10H).
6,6-Diphenyl-5-Decanone (24). This ketone was synthesized as a starting substrate for future analysis of the cathodic cleavage of 1,1-diphenyl ketones. To a 50 mL three-neck round bottom flask equipped with a stir bar, condenser, and drying tube was added 15 mL CH$_2$Cl$_2$, 2.5479 g (3.8965x10$^{-2}$ mol) zinc dust, 1.0406 g (6.4144x10$^{-3}$ mol) valerophenone, and 3.20 mL (2.7932x10$^{-2}$ mol) silicon tetrachloride. The reaction was allowed to stir for 21 hours at room temperature before the mixture was poured onto water and filtered. The filtrate was extracted with CH$_2$Cl$_2$ and dried over Na$_2$SO$_4$. The solvent was removed *in vacuo* to yield 0.7422 g of a reddish-brown liquid, which was further purified via column chromatography (50:50 hexanes:dichloromethane) to give 0.3111 g of pure product as a yellow oil. % yield = 31.44%; GC: rt = 13.771 min; MS: m/z 279, 265, 252, 237, 223, 193, 181, 167; $^1$H NMR (300 MHz, CDCl$_3$): δ 0.64-1.40 (m, 14H), 2.26 (m, 4H), 7.20-7.40 (m, 10H).
**CH\textsubscript{3}CDOHCH\textsubscript{3} (26).** This compound was synthesized to be used as a deuterium atom donor in a divided-cell electrolysis in order to determine whether the cathodic cleavage of 1-methyl-1,1-diphenylacetone (22) involves the formation of a carbanion or radical intermediate. To a 100 mL three-neck round bottom flask equipped with a stir bar, condenser, and drying tube was added 40 mL of dry diethyl ether and 0.5026 g (1.197x10\textsuperscript{-2} mol) lithium aluminum deuteride.\textsuperscript{25} The reaction was cooled in an ice bath and 1.3836 g (2.3822x10\textsuperscript{-2} mol) acetone was added dropwise. The mixture was then left to stir overnight. The mixture was then carefully quenched with brine, extracted with diethyl ether, and dried over Na\textsubscript{2}SO\textsubscript{4}. Distillation of this mixture yielded 0.2168 g of the desired 2-deuterio-2-propanol. % yield = 15\%; \textsuperscript{1}H NMR (300 MHz, CDCl\textsubscript{3}); δ 1.18 (m, 6H), 1.70 (s, 1H), residual diethyl ether solvent peaks, and no observable methine peak.

C. Mechanistic Studies of the Conversion of 1,1-Diphenylacetone (1) to Benzophenone (2) by Electrochemical and Chemical Methods

The cathodic conversion of 1,1-diphenylacetone (1) to benzophenone (2) was investigated using a variety of electrochemical and chemical experiments. The procedures are detailed in this section.
I. Control Experiments

Attempted Autoxidation of 1,1-Diphenylacetone (1). To control for possible conversion of 1 to 2 via an aerobic mechanism similar to the autoxidation of diphenylacetaldehyde (3) to 2, 1 was allowed to react with air for a period of three weeks. To a 25 mL three-neck round bottom flask equipped with a stir bar was added 0.2024 g (9.626x10^{-4} mol) 1 in approximately 20 mL of dry electrolyte solvent (0.1M Bu_4NBF_4 in CH_3CN). Atmospheric oxygen was bubbled through solution, and the reaction mixture was allowed to stir continuously for three weeks. Additional solvent was added as needed during this period to ensure the reaction did not run dry. Mass spectroscopic analysis showed no conversion of 1 to 2. GC: rt = 11.034 min (1); MS: m/z (1) 210 ([M]^{+}), 167, 165, 152.

Constant Current Oxidation of 1,1-Diphenylacetone (1) in the Presence of 2-Phenylethanol. As another control experiment to ensure that 1 is converted to benzhydryl phenethyl ether (11) at the anode, the oxidation of 1 was carried out in the presence of 2-phenylethanol in a divided cell. To the anode compartment was added 0.3661 g (1.741x10^{-3} mol) 1 and 0.2747 g (2.249x10^{-3} mol) 2-phenylethanol in 80 mL of dry electrolyte solvent. The anode compartment was degassed with nitrogen for 30 minutes before the current was turned on at 25 mA. The constant current electrolysis took five hours to attain complete formation of (11), except for a small amount of unreacted ketone. GC: rt = 11.027 min (1), 14.171 min (11); MS: m/z (1) 210 ([M]^{+}), 167, 165, 152; (11) 288 ([M]^{+}), 183, 167, 165, 152.
II. Electrolyses

**Constant Current Electrolysis of 1,1-Diphenylacetone (1) under Nitrogen at the Cathode.** To determine the effect atmospheric oxygen has on the constant current electrolysis of 1 at the cathode, 0.5764 g (2.741x10⁻³ mol) 1 was placed in approximately 75 mL nitrogen-purged electrolyte solution in a divided cell, and the reaction was carried out under continuous nitrogen for the duration of the electrolysis. The reaction was monitored every 30 minutes by GC-MS, which showed conversion of 1 to benzophenone (2) despite bubbling nitrogen through the solution. In addition, diphenylmethane (16) and benzhydryl acetate (14) were observed to appear in solution after 60 minutes. Compounds 16 and 14 were identified and characterized by GC-MS analysis and comparison to spectra of pure samples and samples synthesized using alternative methods (see Section D). The electrolysis took 270 minutes to reach completion, during which the peak corresponding to benzhydryl acetate disappeared and the peak corresponding to diphenylmethane grew. This electrolysis was repeated, and similar results were obtained. GC: rt = 9.053 min (16), 10.434 min (2); MS: m/z (16) 168 ([M]⁺), 167, 165, 153, 152; (2) 182 ([M]⁺), 105, 77.

**Constant Current Electrolysis of 1,1-Diphenylacetone (1) under Atmospheric Oxygen at the Cathode.** With 2 still continuing to form electrochemically at the cathode when nitrogen is bubbled through solution containing 1, it was decided that a constant current electrolysis should be carried out with air being bubbled through solution instead. To the cathode compartment of a divided cell was added 0.5777 g (2.747x10⁻³ mol) 1 in approximately 70 mL dry electrolyte solution. Oxygen was added to the reaction by bubbling air through
solution for 20 minutes prior to turning on the current. The reaction solution remains a pale yellow color throughout the electrolysis. The progress of the reaction was monitored periodically by GC-MS analysis. At 157 minutes, most of 1 had been converted to 2, but the electrolysis was continued for another 48 minutes (total time is 205 minutes) to ensure complete conversion of 1 to 2. Worth noting is that a small benzhydryl acetate peak did make an appearance in the GC spectra but disappeared by the end of the reaction. Diphenylmethane was not observed at any point in the reaction. GC: rt = 10.415 min (2); MS: m/z (2) 182 ([M]+), 105, 77.

**Reaction of 1,1-Diphenylacetone (1) with Pre-Electrolyzed Oxygen.** This reaction was carried out to determine whether a dioxygen species generated *in situ* from the reduction of atmospheric oxygen is responsible for the conversion of 1 to 2. To the cathode compartment of a divided cell was added approximately 70 mL dry electrolyte solution. Air was bubbled through the solution for 30 minutes to ensure saturation before the current was turned on at 25 mA for approximately the same amount of time it took for the conversion of 1 to 2 in the above reactions (200 minutes). The solution turned a pale yellow color after 60 minutes. At the end of 200 minutes, the current was turned off, and 0.5714 g (2.717x10⁻³ mol) 1 was added to solution. Mass spectroscopic analysis of a sample taken immediately after addition of 1 already shows formation of 2 in the pre-electrolyzed solution. The reaction was allowed to stir overnight in the absence of current, and a GC-MS spectrum was taken after 14 hours. The reaction was stopped after 40 hours. GC: rt = 10.434 min (2), 11.040 min (1); MS: m/z (2) 182 ([M]+), 105, 77; (1) 210 ([M]+), 167, 165, 152.
Constant Current Electrolysis of Benzhydryl Acetate (14) at the Cathode

– Attempted. In order to understand the conversion of 1 to 2, the reduction of 14 was attempted. The latter had been observed as a small peak in all the mass spectra involving the conversion of 1 to 2, so to determine whether 14 is an intermediate or is simply a byproduct being converted to a species not seen in the spectra, 0.3990 g (1.763x10^-3 mol) 14 was placed in the cathode compartment of a divided cell with 70 mL of electrolyte solvent. The reduction was monitored periodically by GC-MS, which showed the appearance of a small peak corresponding to diphenylmethane (16) and several unidentified byproducts after 30 minutes. After 120 minutes, unreacted benzhydryl acetate was still the major product, with the diphenylmethane peak having grown slightly. However, by 240 minutes, the benzhydryl acetate peak had disappeared completely and multiple products were present. Because the smaller peaks on the GC spectrum have mass spectra exhibiting parent peaks above m/z 400, which is unlikely due to their low retention times, these peaks have been omitted here. GC: rt = 8.621 min (E), 9.171 min (16), 10.565 min (2); MS: m/z (E) 164, 119, 105, 91; (16) 168 ([M]⁺), 167, 153, 152; (2) 182 ([M]⁺), 105, 77.

Constant Current Electrolysis of 1,1-Diphenylacetone (1) in the Presence of H₂¹⁸O. To the cathode compartment of a divided cell was added 75 mL dry electrolyte solvent, 0.5779 g (2.748x10^-3 mol) 1, and 100 μL (5.544x10^-3 mol) H₂¹⁸O. Nitrogen was bubbled through solution for one hour prior to turning on the current. The reaction took 210 minutes to reach completion, at which mass spectroscopic analysis showed incorporation of¹⁸O into approximately 25% of benzophenone (2) formed. A large peak with a retention time and fragmentation pattern coinciding with
authentic samples of diphenylmethane was also present in the GC spectrum. GC: rt = 9.209 min (16), 10.465 min (2); MS: m/z (16) 168, 167, 153, 152; (2) 184 ([¹⁸O M]⁺‡), 182 ([M]⁺), 105, 77.

**Constant Current Electrolysis of 2-Methyldiphenylmethane (17) and 1,1-Diphenylacetone (1) at the Cathode.** To investigate whether diphenylmethane (16) could be an intermediate in the conversion of 1 to benzophenone (2), equimolar amounts of 1 and 2-methyldiphenylmethane (17) were placed in the cathode of a divided cell, and the reaction was monitored using GC-MS. If diphenylmethane (16) was indeed an intermediate, equal amounts of 2 and 2-methylbenzophenone would appear in the mass spectrum. To the cathode compartment was added 75 mL electrolyte solvent and equimolar amounts of diphenylacetone (0.4212 g; 2.003x10⁻³ mol) and 2-methyldiphenylmethane (17) (0.3597 g; 1.973x10⁻³ mol). The reaction was allowed to proceed, with stirring, for 3 hours. GC: rt = 9.740 min (17); 10.446 min (2); MS: m/z (17) 182 ([M]⁺), 167, 152, 104, 89, 77; (2) 182 ([M]⁺), 105, 77, 51.

**Constant Current Electrolysis of Diphenylmethane (16) and 1,1-Diphenylacetone (1) at the Cathode.** In order to check that steric effects did not play a role in preventing 2-methyldiphenylmethane (17) from being converted to 2-methylbenzophenone in the divided-cell reduction, pure diphenylmethane (16) was placed in the cathode compartment with 1 and the current was turned on. To the cathode compartment of the divided cell was added 75 mL electrolyte solvent and equimolar amounts of 1 (0.4208 g; 2.001x10⁻³ mol) and diphenylmethane (16) (0.3304 g; 1.964x10⁻³ mol). The reaction was allowed to proceed, with stirring, for 6
hours and 3 minutes. GC: rt = 9.021 min (16); 10.446 min (2); MS: m/z (16) 168 ([M]⁺), 167 ([M-H]⁺), 152, 115, 91; (2) 182 ([M⁺]), 152, 105, 77, 51.

III. Chemically-Generated Superoxide Reactions

As a check to the electrochemical experiments detailed in the previous section, reactions using chemically-generated superoxide ions were performed. These reactions give additional information about the nature of the electrochemical reactions. All reactions were carried out using a 5:2.5:1 ratio of KO₂:Et₄NBr:substrate unless otherwise noted. Procedures for these reactions are detailed in this section.

Reaction of 1,1-Diphenylacetone (1) with KO₂. To a 100 mL three-neck round bottom flask equipped with a stir bar, condenser, drying tube, and nitrogen inlet was added approximately 35 mL anhydrous DMF, 1.05 g (1.48x10⁻² mol) potassium superoxide, and 1.68 g (7.99x10⁻³ mol) tetraethylammonium bromide. The solution was allowed to stir for 15 minutes under nitrogen to facilitate dissolution of the solids. After most of the solids appear to have dissolved, 0.6350 g (3.020x10⁻³ mol) 1 was added. The reaction was stopped after 18 hours, at which TLC and GC-MS analysis showed the reaction had gone to completion. For the workup, 20 mL saturated NaCl solution and another 20 mL saturated sodium bicarbonate solution were used to decompose the unreacted KO₂. The product was extracted four times using diethyl ether, and the organic layers were combined and washed with water before being dried over Na₂SO₄. The solvent was removed in vacuo to yield 0.5353 g crude yellow oil. The product was purified further using flash chromatography (95:5 hexanes:ethyl acetate) to yield 0.3246 g final product. % yield = 59%; GC: rt =
10.415 min (2); MS: $m/z$ (2) 182 ([M]$^{+}$), 105, 77; $^1$H NMR (300 MHz, CDCl$_3$): $\delta$
7.40-7.80 (m, 10H).

**Reaction of 2-Methylidiphenylmethane (17) and 1,1-Diphenylacetone (1) with KO$_2$.**

To a 100 mL three-neck round bottom flask equipped with a stir bar, condenser, drying tube, and nitrogen inlet was added 35 mL anhydrous DMF, 1.0795 g (1.5183x10$^{-2}$ mol) KO$_2$, and 1.7011 g (8.0943x10$^{-3}$ mol) Et$_4$NBr. After the reaction was allowed to stir for 15 minutes, 0.3163 g (1.504x10$^{-3}$ mol) 1 and 0.2802 g (1.537x10$^{-3}$ mol) 2-methylidiphenylmethane (17) were added. The reaction was allowed to stir for 43 hours at room temperature before a sample was prepared and analyzed using GC-MS. GC: rt = 9.790 min (17); 10.496 min (2); 10.702 min (2-methylbenzophenone); MS: $m/z$ (17) 182 ([M]$^{+}$), 167, 152, 104; (2) 182 ([M]$^{+}$), 152, 105, 77, 51; (2-methylbenzophenone) 195 ([M-H]$^{+}$), 182, 119, 105, 77.

**Reaction of Diphenylacetaldehyde (3) with KO$_2$.** This reaction was carried out in order to test whether diphenylacetalddehyde reacts with superoxide in the same manner as 1. Instead of Et$_4$NBr, Bu$_4$NBr was used as the phase transfer catalyst in this reaction. The ratio of reagents was kept the same as previous reactions. To a 100 mL three-neck round bottom flask equipped with a stir bar, condenser, drying tube, and nitrogen inlet was added 35 mL anhydrous DMF, 1.0617g (1.4932x10$^{-2}$ mol) KO$_2$, and 2.5734 g (7.9828x10$^{-3}$ mol) Bu$_4$NBr. The mixture was allowed to stir for 15 minutes before 0.5876 g (2.994x10$^{-3}$ mol) 3 was added. The sample of 3 used in this reaction was from a new bottle and was analyzed using GC-MS prior to use to ensure that benzophenone (2) had not already formed from the autoxidation of 3 by molecular oxygen. The reaction was stirred for an additional 13 hours at room
temperature before a sample was prepared and analyzed using GC-MS. GC: rt = 10.415 min (2); MS: m/z (2) 182 ([M]+), 152, 105, 77.

**Reaction of 1,1-Diphenylacetone (1) with Na₂O₂.** The reaction between 1 and sodium peroxide was carried out under the similar conditions as those used for the reaction between 1 and KO₂ but with Na₂O₂ as the primary oxygen donor. To a 100 mL three-neck round bottom flask equipped with a stir bar, condenser, drying tube, and nitrogen inlet was added 30 mL DMF, 0.5849 g (7.501x10⁻³ mol) Na₂O₂, and 1.2895 g (4.0001x10⁻³ mol) Bu₄NBr. After stirring for 15 minutes, much of the Na₂O₂ remained undissolved, but 0.3127 g (1.487x10⁻³ mol) 1 was still added. Upon addition of 1, the mixture immediately turned from colorless to yellow. The reaction was allowed to stir for 24 hours before a sample was prepared and analyzed using GC-MS. GC-MS analysis indicated that significant amounts of 1 were still present, so the reaction was allowed to stir for longer. The reaction took two weeks to reach completion, and mass spectroscopic analysis indicated presence of a large peak corresponding to 2 and a small peak corresponding to a compound with a parent ion of m/z 214. GC: rt = 10.402 min (2), 12.733 min; MS: m/z (2) 182 ([M]+), 105, 77; 214, 197, 180, 167.

**D. Mechanistic Studies of the Cleavage of Various α-Substituted Diphenyl Ketones**

To investigate whether the cleavage of α-substituted diphenyl ketones occurs by electrogenerated superoxide, electrolyses at the cathode and reactions with KO₂ were carried out. The procedures are outlined in detail in this section.
I. Electrolyses

**Constant Current Electrolysis of 1-Methyl-1,1-Diphenylacetone (22) at the Cathode.** To the cathode compartment of a divided cell was added 75 mL of dry electrolyte solvent and 0.3418 g (1.524x10^{-3} mol) 22. The solution was purged with oxygen 30 minutes prior to turning on the current. During the electrolysis, the current kept decreasing and reached 8 mA in the first hour. Due to the changing current and the high voltage required to carry out the reaction, the electrolysis was started and stopped multiple times over three days. The reaction was monitored periodically using GC-MS and took 10 hours to reach completion, yielding 0.0798 g of product, which was characterized to be 1,1-diphenylethane (23). % yield = 29%; GC: rt = 9.452 min; MS: m/z (23) 182 ([M]+), 167, 165, 152; ^1^H NMR (300 MHz, CDCl₃): δ 1.62 (d, 3H), 4.18 (q, 1H), 7.18-7.42 (m, 10H).

**Constant Current Electrolysis of 1-Methyl-1,1-Diphenylacetone (X) in the Presence of D₂O at the Cathode.** In order to determine whether 22 is converted to 1,1-diphenylethane (23) via a carbanion or radical intermediate, constant current electrolyses were carried out in the presence of a deuterium ion or atom donor, respectively. D₂O was employed as a deuterium ion donor. To the cathode compartment of the divided cell was added 75 mL of electrolyte solvent, 0.3249 g (1.448x10^{-3} mol) 22, and 0.3059 g (200 mM) D₂O. The reaction was allowed to proceed for 12 hours, during which the current kept decreasing from 25 mA to 0 mA. 22 may experience high adsorption, thus increasing the resistance and decreasing the current. Despite attempts at using a new conducting gel and carbon cloth, the same drop in current occurred, and the reaction was stopped after 12 hours. GC-MS
analysis showed that deuterium was not incorporated into the 23 formed. GC: rt = 9.453 min (23); 11.365 min (22); MS: m/z (23) 182 ([M]⁺), 167, 152, 77; (22) 224 ([M]⁺), 181, 165, 103, 77.

**Constant Current Electrolysis of 1-Methyl-1,1-Diphenylacetone (22) in the Presence of CH₃CDOHCH₃ at the Cathode.** CH₃CDOHCH₃ was used as a deuterium atom donor. To the cathode compartment of the divided cell was added 75 mL of electrolyte solution, 0.4129 g (1.841x10⁻³ mol) 22, and 0.2168 g (47 mM) 2-deuterio-2-propanol. The reaction was allowed to proceed for 14 hours and 25 minutes before it was stopped. During the course of the reaction, the current continued to decrease from 25 mA to 0 mA, despite using a new conducting gel and carbon cloth and pausing the flow of current for extended periods of time. The reaction was continued until enough mass spectroscopic data were obtained. The mass spectrum of 23 indicated that no deuterium was incorporated. GC: rt = 9.484 min (23); 11.340 min (22); MS: m/z (23) 182 ([M]⁺), 167, 152, 77; (22) 224 ([M]⁺), 181, 165, 103, 77.

**Constant Current Electrolysis of 2,2,2-Triphenylacetophenone (19) at the Cathode.** To the cathode compartment of a divided cell was added 75 mL of dry electrolyte solvent and 0.2882 g (8.271x10⁻⁴ mol) 2,2,2-triphenylacetophenone (19). The solution was purged with oxygen for 30 minutes before the current was turned on. During the electrolysis, the current kept fluctuating, at which point the reaction was paused and re-started. The reaction was monitored using GC-MS and took 251 minutes to reach completion, yielding 0.1575 g of product, which was identified to be
triphenylmethane (20). % yield = 78%; GC: rt = 12.739 min (20), 13.602 min (21); MS: \[m/z\] (20) 244 ([M]+), 167, 166, 165, 152; (21) 260 ([M]+), 183, 165, 154, 105.

**Constant Current Electrolysis of 6,6-Diphenyl-5-Decanone (24) at the Cathode.** To the cathode compartment of a divided cell was added 0.3100 g (1.005x10^{-3} \text{ mol}) 24 in 75 mL of electrolyte solvent. The solution was purged with air for 20 minutes prior to turning on the current at 25 mA. During the electrolysis, the resistance began to increase, thus increasing the voltage and decreasing the current. The reaction was paused multiple times and resumed after replacing the carbon cloth electrodes. Despite these changes, the current continued to decrease, so the reaction was stopped after 28 hours. GC-MS analysis showed equal sized peaks corresponding to 24 and the expected product, 1,1-diphenylpentane (25). No isolated yield was obtained. GC: rt = 11.183 min (25); 12.133 min (L); 13.770 min (24); MS: \[m/z\] (25) 224 ([M]+), 167, 152; (L) 222, 193, 183, 105; (24) 223, 167, 119.

**II. Chemically-Generated Superoxide Reaction**

**Reaction of 1-Methyl-1,1-Diphenylacetone (22) with KO\(_2\).** To a 50 mL three-neck round bottom flask equipped with a stir bar, condenser, and nitrogen inlet was added 15 mL of anhydrous DMF, 0.5375 g (7.560x10^{-3} \text{ mol}) KO\(_2\), and 0.8149 g (3.878x10^{-3} \text{ mol}) Et\(_4\)NBr. The mixture was stirred for 20 minutes before 0.3238 g (1.443x10^{-3} \text{ mol}) 22 was added. The reaction was allowed to stir for an additional 65 hours, and the progress of the reaction was monitored using GC-MS. Results showed that there was still a significant amount of 22 in solution. An additional 0.8081 g KO\(_2\) and 1.1805 g Et\(_4\)NBr were added to drive the reaction to completion. The reaction proceeded for 2 weeks before GC-MS results showed complete disappearance of
starting material. GC: rt = 9.434 min (23); 9.659 min; 10.496 min; MS: m/z (23) 182
References


