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Dimethylsulfoxide as a kinetic booster for the chemical generation of singlet oxygen in methanol

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ABSTRACT

The kinetic booster effect of dimethylsulfoxide on the chemical generation of singlet oxygen, $^1O_2$, from the disproportionation of hydrogen peroxide catalyzed by molybdate ions in methanol has been evidenced by detection of the IR luminescence of $^1O_2$ at 1270 nm and by ^{95}Mo NMR spectroscopy. DMSO interacts rapidly, through a direct oxygen transfer with the stable tetraperoxomolybdate $Mo(O_2)_4^{2-}$, leading to $DMSO_2$ and to the unstable triperoxomolybdate $Mo(O_2)_3^{2-}$, which releases $^1O_2$. The procedure was applied to accelerate the dark singlet oxygenation of β-citronellol and α-terpinene.

1. Introduction

Singlet oxygen, $^1O_2$ ($^1\Delta_g$), can be chemically generated from hydrogen peroxide disproportionation catalyzed by molybdate ions in alkaline aqueous solutions.[1] Four peroxomolybdates, $MoO_{4-n}(O_2)_n^{2-}$ with $n = 1, 2, 3, 4$, are formed under these conditions but the triperoxomolybdate, $MoO(O_2)_3^{2-}$, is the main precursor of $^1O_2$ whereas the tetraperoxomolybdate $Mo(O_2)_4^{2-}$ is stable.[2]

This reaction has been implemented in organic solvents, especially in dipolar protic solvents, such as methanol, for the 'dark' singlet oxygenation of hydrophobic substrates.[3] In such solvents, a continuous and slow addition of H_2O_2 is required for an optimal reaction kinetics in order to favor the formation of $MoO(O_2)_3^{2-}$ and to avoid that of $Mo(O_2)_4^{2-}$. This procedure has been scaled up by DSM company in 10 m^3 reactors to produce rose oxide from β-citronellol in ethylene glycol.[4]

On the other hand, the screening of various solvents had revealed a puzzling behavior for DMSO as the chemiluminescence signal of $^1O_2$ was intense (≈285 mV) but much shorter (≈2 min) than in other solvents, strongly suggesting that DMSO interferes with the chemical generation of $^1O_2$ or with $^1O_2$ itself.[3] However, several papers report that sulfoxides do not react chemically with $^1O_2$ to give the corresponding sulfone,[5] while they interact with peroxomolybdates at a very low reaction rate.[6]

Hence, in the present work, we reexamine the mechanism of $^1O_2$ generation from the H_2O_2/MoO_4^{2-}/DMSO system in methanol by monitoring the formation of $^1O_2$ through its IR chemiluminescence[7] and by detecting the intermediate peroxomolybdates involved in the process by ^{95}Mo NMR. Then, we take advantage of the accelerating effect of DMSO to speed up the 'dark' singlet oxygenation of α-terpinene and β-citronellol in MeOH.

2. Experimental

2.1. NIR-chemiluminescence spectrometer

All measurements of light emission attributable to the chemiluminescent transition of $^1O_2$ to the triplet ground state were carried out in the near infrared (NIR) at 1270 nm with a home-made instrument fitted with a liquid nitrogen-cooled germanium photodiode detector (Model EO-817L, North Coast Scientific Co., Santa Rosa, CA, USA) sensitive in the spectral region from 800 to 1800 nm with a detector of 0.25 cm^2 and a sapphire window.[7]

2.2. Typical luminescence experiments

A solution of $Na_2MoO_4 \cdot 2H_2O$ (121.0 mg, 0.05 M, 0.5 mmol) in MeOH (10 mL) was placed in the thermostated brass cell holder at 25 °C. When the background noise of the IR signal was stabilized, H_2O_2 (50%, 600 μL, 1 M, 10 mmol) was introduced and the intensity of the luminescence signal was recorded. After 10 min, DMSO (360 μL, 0.5 M, 5 mmol) was added in the solution.

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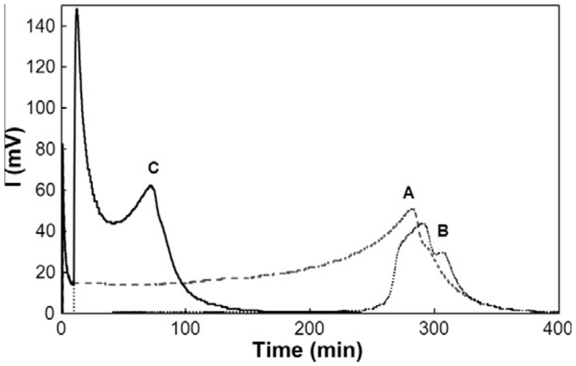


Figure 1. IR luminescence at 1270 nm of $^1O_2$ generated at 25 °C from solutions containing Na_2MoO_4 0.05 M and H_2O_2 1 M in MeOH alone (A) or after addition of α-terpinene 0.25 M (B) or DMSO 0.25 M (C).

2.3. Oxidation experiments

A solution of $Na_2MoO_4 \cdot 2H_2O$ (36.3 mg, 0.15 mmol), DMSO (106 μL, 1.5 mmol), and the substrate (1.5 mmol) in MeOH (2.5 mL) was placed in a thermostated water bath at 25 °C, after which aqueous H_2O_2 (50%, 180 μL, 3 mmol) was added. The orange-red reaction medium was stirred until it became almost colorless while the disappearance of substrate was followed by ^1H NMR analysis of the reaction mixture.

3. Results and discussions

3.1. Effect of DMSO on singlet oxygen production from H_2O_2/MoO_4^{2-}

The influence of the addition of an efficient trap of $^1O_2$, α-terpinene, and of DMSO on the IR-luminescence signal arising from the H_2O_2/MoO_4^{2-} system in MeOH was first studied (Fig. 1).

At high H_2O_2/Mo ratios, MoO_4^{2-} is mainly converted into the stable $Mo(O_2)_4^{2-}$, beside a minor amount of $MoO(O_2)_3^{2-}$ which is responsible for the weak luminescence (≈18 mV) (curve A). As the reaction proceeds, H_2O_2 is slowly consumed and the equilibrium between $Mo(O_2)_4^{2-}$ and $MoO(O_2)_3^{2-}$ is shifted toward the less peroxidized intermediate. Accordingly, the dark red solution fades into orange while the $^1O_2$ signal progressively increases in such a way that a maximum of intensity (≈55 mV) is reached at ≈5 h. When α-terpinene is added to the medium (curve B), the signal sharply drops reflecting the chemical trapping of $^1O_2$ by the substrate as expected. Once all α-terpinene has been consumed, the signal is almost recovered since the product formed, that is, ascaridole, does not interfere with the formation or the decomposition of peroxomolybdates. On the contrary, when DMSO is added (curve C), the signal is dramatically different resulting in a 10-fold higher intensity corresponding to a sudden burst of $^1O_2$ production. This result strongly suggests that DMSO directly interacts with the red-brown $Mo(O_2)_4^{2-}$ giving the orange $MoO(O_2)_3^{2-}$, which, in turn, rapidly decomposes into $^1O_2$. It is noteworthy that DMSO does not react chemically with $^1O_2$ as evidenced by its lifetime in this solvent (τ_Δ = 19 μs).[8] Bunton and co-workers. reported the fading of a tetraperoxomolybdate solution by the addition of thioanisole and explained it by a direct oxygen transfer from $Mo(O_2)_4^{2-}$ to the sulfide leading to its oxidation into the corresponding sulfoxide.[6] However, in contrast to our observation with DMSO, they also reported that the oxidation of the sulfoxide itself by the tetraperoxomolybdate into the corresponding sulfone is very slow. DMSO appears then much more reactive toward $Mo(O_2)_4^{2-}$ than the aryl sulfoxide. The main characteristics of the chemiluminescence curves as a function of DMSO concentration are reported in Table 1.

3.2. Mechanism of $^1O_2$ production

The disappearance of DMSO (0.25 and 0.5 M) was followed by ^1H NMR in methanol-*d*$_4$ containing Na_2MoO_4 (0.05 M) and H_2O_2 (1 M) (see Supplementary data). The reaction is first order in each reactant and leads to the total conversion of DMSO into $DMSO_2$ after 30 min. ^{95}Mo NMR experiments were then carried out in CH_3OD to determine the nature of the peroxomolybdates involved in the process.

Tetrabutylammonium salt, $(NBu_4)_2MoO_4$, was used to increase the catalyst solubility in methanol and the medium was maintained at 0 °C to slow down the peroxomolybdate decomposition. NMR spectra reported in Figure 2 clearly show that the addition of DMSO to the red-brown solution of $Mo(O_2)_4^{2-}$ (spectrum F) gives, almost instantaneously, the triperoxomolybdate $MoO(O_2)_3^{2-}$ (spectrum E). As a reference, curve D shows a mixture of tri- and tetra-peroxomolybdates obtained by mixing MoO_4^{2-} with a lower concentration of H_2O_2. These findings led us to propose the mechanism described in Scheme 1 accounting for the boosting of $^1O_2$ from the H_2O_2/MoO_4^{2-} system in MeOH in the presence of DMSO.

The quenching of $Mo(O_2)_4^{2-}$ by DMSO probably occurs through a direct oxygen transfer from one peroxo group to the sulfoxide as reported by Bunton in the case of thioanisole.[6] Kinetically, the addition of DMSO leads to an increase of the decomposition rate of H_2O_2 by a factor of 3–7 depending on the added concentration.

Table 1
Effect of DMSO on the chemiluminescence signal of $^1O_2$ generated from the H_2O_2/MoO_4^{2-} system in methanol. Conditions: $[Na_2MoO_4]_0$ = 0.05 M, $[H_2O_2]_0$ = 1 M, 25 °C

Entry	[DMSO] (M)	Curve	Δt_{end}[f] (min)	Area (mV min)	$^1O_2$ yield[g] (%)	V $^1O_2$[i] (mM min^{-1})
1	0	A	336	7320	70[h]	1.0
2	0	B[d]	337	2550	–	1.0
3	0.25[a]	C	117	5290	51	2.2
4	0.5[a]	[e]	59	3800	36	3.0
5	0.5[b]	[e]	60	3830	37	3.0
6	2 x 0.25[c]	[e]	61	3730	36	2.9

[a] DMSO added 10 min after H_2O_2.
[b] DMSO added before H_2O_2.
[c] DMSO added at 10 and 20 min after H_2O_2.
[d] Addition of α-terpinene 0.25 M.
[e] Curves presented in Supplementary data.
[f] Corresponding to a residual signal intensity equal to 5 mV.
[g] $[^1O_2]_{cumulative}/0.5 \times [H_2O_2]_o$ calculated from the underlying area of the luminescence curve.
[h] According to Ref. 3.
[i] $[^1O_2]_{cumulative}/\Delta t_{end}$.

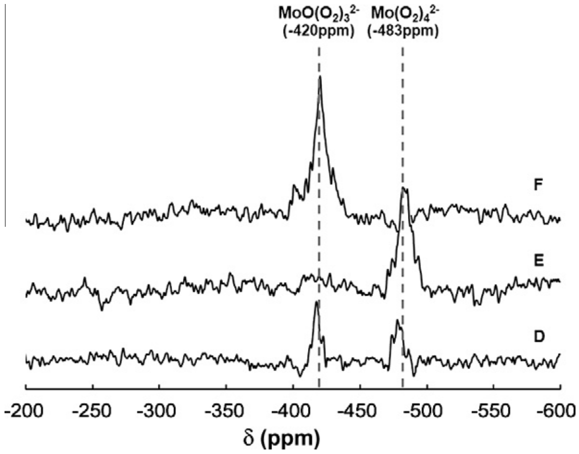
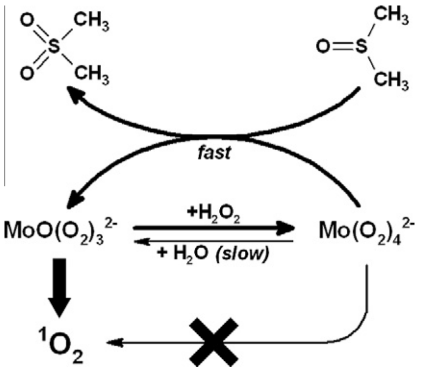


Figure 2. ^{95}Mo NMR spectra at 0 °C of solutions in CH_3OD of $(NBu_4)_2MoO_4$ 0.1 M and 1 M H_2O_2 (D), $(NBu_4)_2MoO_4$ 0.2 M and 3 M H_2O_2 without DMSO (E) or with 1.5 M DMSO (F). $Mo(O_2)_4^{2-}$ and $MoO(O_2)_3^{2-}$ signals are assigned from Ref. 2.



Scheme 1. Mechanism of $^1O_2$ generation from H_2O_2/MoO_4^{2-} in the presence of DMSO.

This acceleration is probably due to the shunt of the slow hydrolysis of $Mo(O_2)_4^{2-}$ into $MoO(O_2)_3^{2-}$ by the rapid quenching of $Mo(O_2)_4^{2-}$ by DMSO leading to the formation of $MoO(O_2)_3^{2-}$ that rapidly releases $^1O_2$. The dramatic effect of DMSO on $Mo(O_2)_4^{2-}$ is clearly shown by monitoring the fading of the red-brown tetraperoxo species by visible spectroscopy at 600 nm (Fig. 3).

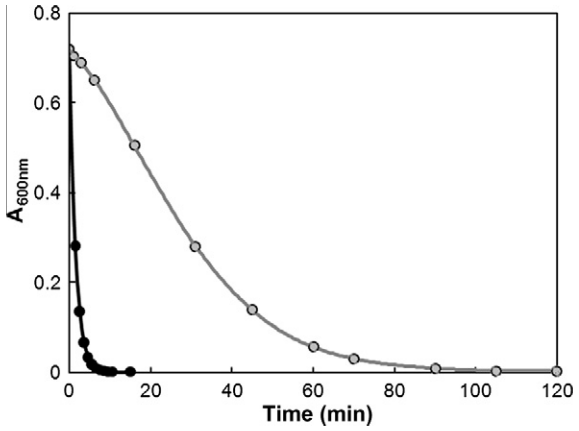


Figure 3. Evolution of the absorbance at 600 nm of $Na_2Mo(O_2)_4$ 0.02 M in MeOH alone (gry) or with DMSO 0.25 M (black) at 25 °C.

Table 2

Effect of DMSO on the peroxidation of β-citronellol 0.20 M and α-terpinene 0.25 M by the H_2O_2/MoO_4^{2-} system in MeOH. Conditions: $[Na_2MoO_4]$ = 0.05 M, $[H_2O_2]$ = 1[a] or 2[b] M, conversion ⩾95%, T = 25 °C

Entry	Substrate	(DMSO) (M)	$\Delta t_{95\%}$ (min)	TOF (h^{-1})
1	1[a]	–	450	0.63
2		0.25	165	1.73
3	2[b]	–	850	0.29
4		0.25 × 2	220	1.05

[a] One addition of H_2O_2 1 M.

[b] Two additions of H_2O_2 1 M.

Actually, when $Mo(O_2)_4^{2-}$ 0.02 M in MeOH is kept at 25.0 ± 0.1 °C, it slowly decomposes according to a first order process ($t_{1/2}$ = 77.01 min, $k = 1.5 \times 10^{-4}\ s^{-1}$) whereas its disappearance is about 100 times faster in the presence of 0.25 M DMSO ($t_{1/2}$ = 0.97 min, $k = 1.2 \times 10^{-2}\ s^{-1}$). As a consequence, the yield of $^1O_2$ decreases since the oxidation of DMSO into $DMSO_2$ by $Mo(O_2)_4^{2-}$ consumes a part of H_2O_2 whereas the $^1O_2$ production rate increases by a factor of ≈2.2–3 (Table 1).

It is noteworthy that addition of DMSO in batches (entry 4 vs entry 6) and before or after H_2O_2 (entry 4 vs entry 5) has no influence on the $^1O_2$ yield as well as on the reaction time. However, the profile of the luminescence curves obtained with 1 M of H_2O_2 and 0.5 M of DMSO added before (entry 5) or after H_2O_2 (entry 4) is different (see Figs. 6e and 6f in Supplementary data) although they have the same underlying area. This indicates that the instantaneous rates of $^1O_2$ formation are different in the two cases and mainly result from different compositions of the reaction mixtures. Actually, when DMSO is added 10 min after H_2O_2, the $MoO(O_2)_3^{2-}$/$Mo(O_2)_4^{2-}$ equilibrium is reached and DMSO reacts with the maximum concentration of $Mo(O_2)_4^{2-}$ leading to a high initial $^1O_2$ production rate and to a high signal intensity ($I \approx 300$ mV). On the other hand, when DMSO is added first, a lower initial $^1O_2$ production rate ($I \approx 180$ mV) is obtained, as $Mo(O_2)_4^{2-}$ is continuously being converted into $MoO(O_2)_3^{2-}$ before reaching its maximal concentration. When all DMSO has been consumed, after about 30 min, only the remaining H_2O_2 is responsible for the $^1O_2$ formation. This confirms that the presence of DMSO does not interfere with the kinetics and equilibrium of the peroxomolybdate formation and that the reaction between DMSO and $Mo(O_2)_4^{2-}$ is much faster than the time required to attain the $MoO(O_2)_3^{2-}$/$Mo(O_2)_4^{2-}$ equilibrium.

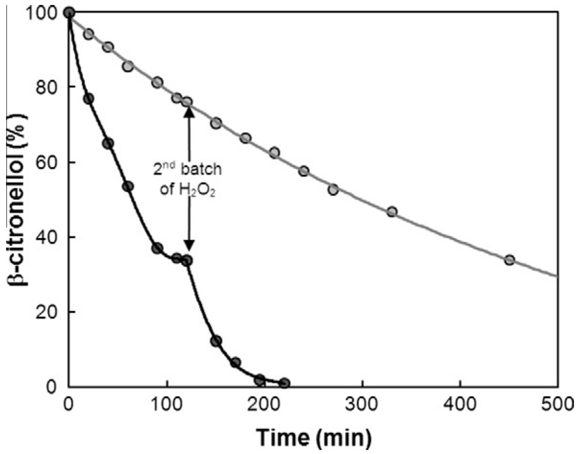


Figure 4. Peroxidation of β-citronellol 0.20 M with two additions of H_2O_2 1 M (gray) and in the presence of DMSO 0.25 M (black). Conditions: methanol, $[Na_2MoO_4]$ = 0.05 M, T = 25 °C.

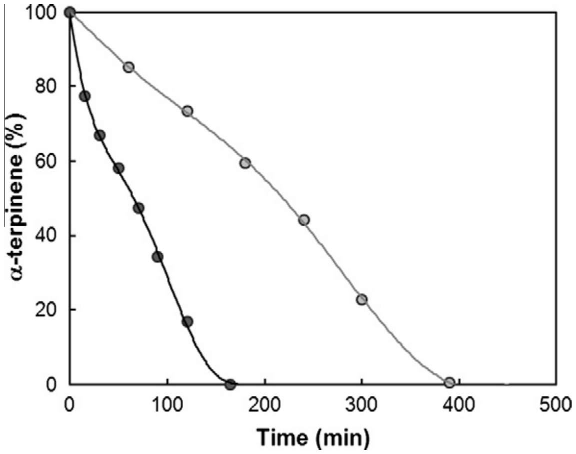


Figure 5. Peroxidation of α-terpinene 0.25 M with H_2O_2 1 M (gray) and in the presence of DMSO 0.25 M (black). Conditions: methanol, $[Na_2MoO_4] = 0.05$ M, $T = 25$ °C.

3.3. Oxidation of α-terpinene and β-citronellol with the system H_2O_2/DMSO/MoO_4^{2-}

This procedure was then applied to the peroxidation of α-terpinene **1** and β-citronellol **2**. Compound **1** reacts with $^1O_2$ according to a [4 + 2] cycloaddition leading to ascaridole whereas **2** provides a mixture of two hydroperoxides according to the ene reaction.[9] Results are reported in Table 2.

Addition of DMSO clearly boosts the rates of peroxidation of substrates in MeOH. At 25 °C, the time required to oxidize more than 95% of β-citronellol is more than three-times shorter when 0.25 M DMSO is added (Fig. 4). In the case of α-terpinene, addition of 0.25 M DMSO accelerates the reaction rate by a factor 2.7 (Fig. 5). In all cases, the reactions lead to the expected oxidation products.

4. Conclusion

The intrinsic reactivity of peroxomolybdates, which may be a drawback because it can lead to side reactions, such as epoxidation, is proved herein to be beneficial as it significantly accelerates the rate of $^1O_2$ production when DMSO is added to the reaction medium. It actually shortens the time required for complete oxidation of the substrate. The process is simple and kinetically improved compared to peroxidations conducted in MeOH without DMSO for which a careful controlled addition of H_2O_2 is required. It is thus an interesting alternative to the more intricate microemulsions[10] for the dark singlet oxygenation of low molecular weight hydrophobic substrates.

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Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tetlet.2010.10.022.

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