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Preparation of pure hydrogen peroxide and anhydrous peroxide solutions from crystalline serine perhydrate

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ABSTRACT

Hydrogen peroxide is one of the most versatile oxidation reagents, still it has not fully been exploited by synthetic chemists since anhydrous (let alone pure) hydrogen peroxide requires hazardous preparation protocols. We have recently reported on the crystallization of serine and other amino acid perhydrates, thus paving the way for a new method for laboratory-scale production of anhydrous hydrogen peroxide solutions. Serine is insoluble in most organic solvents (e.g., methanol, ethyl acetate, and methyl acetate) that readily dissolve hydrogen peroxide. Moreover, since the adduct of hydrogen peroxide and serine is unstable in these organic solvents, crystalline serine perhydrate readily decomposes to give anhydrous solutions of hydrogen peroxide and crystalline precipitate of the amino acid. This procedure can then yield an anhydrous hydrogen peroxide solution in a single step. Moreover, filtration of the amino acid, and room temperature evaporation of the volatile solvent (e.g., methyl acetate), yields over 99% hydrogen peroxide.

1. Introduction

Hydrogen peroxide is an environmentally friendly oxidant, that is, routinely used in fine chemical synthesis, catalysis, and the electronic industry. Anhydrous hydrogen peroxide solution is one of the key reagents for silicon wafers cleaning, etching, epoxidation processes,[1,2] synthesis of organosilicon peroxides[3] and some other peroxocompounds.[4] Pure hydrogen peroxide is mainly used for preparation of peroxo containing crystals[5,6,7,8] and physical studies of the hydrogen peroxide.[9,10] Currently, there are three main obstacles that are limiting an even wider use of hydrogen peroxide by synthetic chemists, including university scholars, who occasionally require small quantities of hydrogen peroxide. (i) Pure hydrogen peroxide, even in laboratory-scale quantities, is commercially unavailable and its synthesis by non experts is hazardous. (ii) Hydrogen peroxide is commercialized with high concentrations of undesirable phosphate, stannate, sulfate or borate preservation agents. (iii) Anhydrous hydrogen peroxide solutions can be prepared by dissolution of organic perhydrate but the organic component remains in the anhydrous H_2O_2 solution.

Since its discovery and first purification by Thenard in 1818[11], the purification of hydrogen peroxide is still a formidable process. Currently, the only viable approaches for obtaining 99% pure, hydrogen peroxide are based on fractional crystallization of hydrogen peroxide, water evaporation or chemical binding and removal of water from aqueous hydrogen peroxide solutions.

Fractional crystallization relies on the low melting point of hydrogen peroxide–water mixture. Supercooling of the mixture crystallizes the mixed hydrogen peroxide–water crystals with enriched hydrogen peroxide content, provided that the initial concentration of hydrogen peroxide is sufficiently high to prevent the formation of hydrogen peroxide monohydrate. This limits the fractional crystallization procedure to starting solutions, which contain over 90% hydrogen peroxide.[12,13]

Distillation of water from hydrogen peroxide solution is based on the difference in vapor pressure of H_2O and H_2O_2 (17.5 vs 1.36 mm Hg at 20 °C).[11] Water evaporation is usually enhanced by performing the operation in a dessicator, over sulfuric acid.[14] A related hydrogen peroxide purification method is based on mixing a highly concentrated hydrogen peroxide aqueous solution (>90%) with diethyl ether, subsequent drying by $CaCl_2$ and phosphorous pentoxide, and final evaporation of the ether.[15] However, significant levels of ether remain in the hydrogen peroxide product.[16] An interesting procedure was reported by Titova et al.,[14] combining the benefits of water capture by magnesium perchlorate, and vacuum distillation of the hydrogen

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peroxide. The hydrogen peroxide is then collected in a liquid nitrogen trap. However, evaporation of hydrogen peroxide should be reserved to well-equipped hydrogen peroxide experts, and avoided by general synthetic chemists.

In short, current methods for obtaining pure hydrogen peroxide fall into two categories: they either involve removal of water, or removal of hydrogen peroxide from aqueous peroxide solutions. Hydrogen peroxide evaporation[17] is hazardous, and water removal[10] concentrates the preservation agents in the hydrogen peroxide product.

Preparation of anhydrous hydrogen peroxide solutions is also a complicated task that bears drawbacks, although several approaches are currently being used. Pure hydrogen peroxide can be used to produce anhydrous solutions in organic solvents, but the obstacles in obtaining pure hydrogen peroxide were discussed above. Another approach to obtaining anhydrous solution is by going through hydrogen peroxide adducts. Dissolution of urea peroxide (percarbamide)[18] or a l:2 complex of 1,4-diazabicyclo[2.2.2] octane (DABCO):hydrogen peroxide[19] is often used to produce anhydrous solutions of hydrogen peroxide. Despite the popularity of these reagents, the organic components remain in the hydrogen peroxide solution and may interfere with catalytic and synthetic studies. In particular, acid–base reactions are influenced by the presence of amines; free radical reactions are biased by side reactions of the reactive oxygen species with the nitrogen containing compounds, and substitution reactions are influenced by the presence of amines in the solution. Perhydrate and transition metal peroxo-complex formation is hindered, or even prevented, by the presence of the organic impurities.

In this article we described a simple and relatively safe approach for obtaining impurity-free, anhydrous organic peroxide solutions. In addition, low temperature vacuum evaporation of the organic solvent leaves >99% pure hydrogen peroxide. Both procedures are very suitable for small scale work, making it possible to obtain minute quantities of anhydrous, or pure hydrogen peroxide, thus reducing the safety concerns even further. The procedure is based on the immersion of organic perhydrate in a solvent that can dissolve hydrogen peroxide, but not the organic moiety or the hydrogen peroxide–organic compound adduct. Until now, there were relatively few reported organic perhydrates and none—to the best of our knowledge—could release the hydrogen peroxide alone into an organic solvent.

Amino acid perhydrates, which were only recently reported,[7] are especially suitable starting materials for the preparation of anhydrous hydrogen peroxide solutions, since the amino acid is insoluble in most organic solvents that dissolve hydrogen peroxide. Additionally, pure crystalline serine perhydrate can be obtained from as low as 70% hydrogen peroxide, which is commercially available, and can also be easily prepared by concentration of the commonly used 50% hydrogen peroxide.

2. Results and discussion

Although, in principle, both glycine and serine perhydrates are suitable for the preparation of anhydrous hydrogen peroxide solutions, the use of serine perhydrate was preferred in this work. This is because pure 1:1 serine perhydrate with no residual water could already be obtained, in less than an hour, from 70% hydrogen peroxide solutions. The serine perhydrate, which forms large crystals of up to several mm, can be washed by anhydrous solvent (e.g., by ethyl acetate or methyl acetate) without decomposition. Serine perhydrate did not decompose in vacuum, and it was stable at 4 °C for a long time (>six months) according to the permanganatometry.

2.1. Preparation of anhydrous hydrogen peroxide solutions

L-serine perhydrate was crystallized from refrigerated aqueous hydrogen peroxide solution saturated with serine. We used 20 g serine in 20 mL of aqueous hydrogen peroxide (containing unspecified concentration of phosphate stabilizer). The perserine was allowed to crystallize at −20 °C for 5 h. The serine perhydrate crystals could be separated from the mother liquor by decantation. Then the crystals were rinsed twice by dry ethyl acetate, and finally dried in a vacuum desiccator for two hours. We received 15 g serine perhydrate. The crystals were stored in a desiccator under refrigeration (−4 °C). The residual serine could be crystallized from the mother liquor with methanol, yielding a mixture of serine and serine perhydrate crystals, which could be reused for serine perhydrate formation.

Anhydrous hydrogen peroxide in ethyl acetate was prepared by adding the perhydrate to ethyl acetate. We introduced 1 g of perhydrate to 10 mL of solvent in an unstirred beaker for two days. Crystal decomposition and hydrogen peroxide release took place. We filtered and recovered the serine crystals by glass filter (Whatman), and the solution, containing 2.6% of anhydrous hydrogen peroxide, was characterized. The recovery of the hydrogen peroxide was quantitative as determined by permanganatometry. The hydrogen peroxide solution can be further concentrated by rotavapor at room temperature.

Figure 1 delineates powder XRD patterns of the serine precipitate (curve a) and the serine perhydrate. The serine and serine perhydrate XRD patterns fit well the X-ray diffractograms that were calculated from single crystal data of serine perhydrate and polymorph I of L-serine. The calculated peaks are depicted by open square symbols on the respective diffractograms. The only exception is a small additional peak at 2θ=13.348° in the recovered serine diffractogram. The peak corresponds to the largest peak in the serine perhydrate pattern (b), and it shows that in this particular case a minor amount of serine perhydrate was still present in

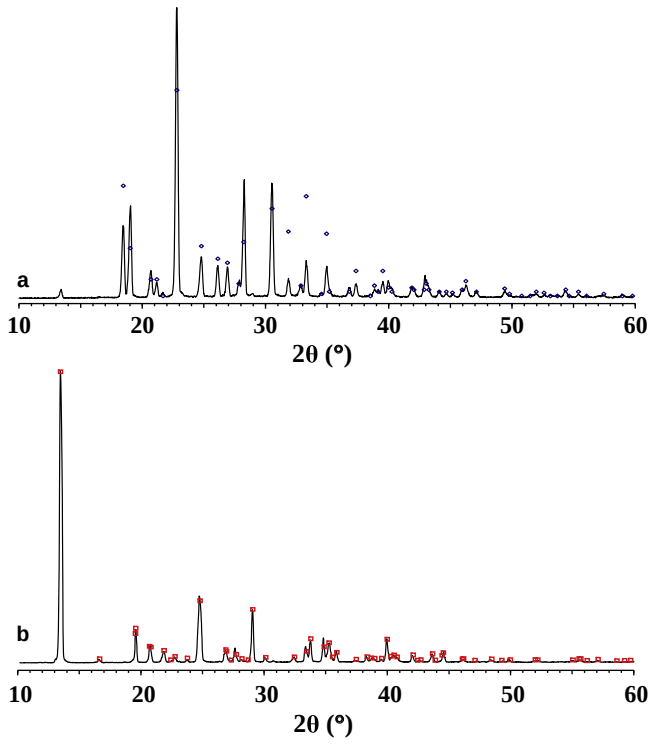

Figure 1. Powder XRD diffractograms of serine precipitate (curve a) obtained after immersion of serine perhydrate (curve b) in ethyl acetate.

the recovered serine crystals. The quantitative disagreement between the observed intensities of the calculated peaks of serine and those in the precipitated serine are attributed to preferential orientation of the serine crystals in the precipitate.

We checked the residual serine in the anhydrous hydrogen peroxide solutions by immersing of 1 g perhydrate in 1–20 mL of methyl or ethyl acetate solvents. In all cases the concentration of serine was less than our limit of quantification, 0.4 mM (which corresponds to serine–hydrogen peroxide ratio <0.003). However, traces of serine, below the quantification limit, could be observed in all samples.

Figure 2 (curve a) demonstrates the ^{17}O NMR spectrum of 11% hydrogen peroxide-ethyl acetate solution prepared from serine perhydrate. The spectrum exhibits three peaks corresponding to ethyl acetate (174.2 and 355.2 ppm) and a 180.4 ppm signal that was assigned to hydrogen peroxide in ethyl acetate. Curve b corresponds to the same solution after spiking with water reaching 0.03:1 H_2O–H_2O_2.

The insert shows a magnified range of the water region. The new signal at −8.7 ppm in the ^{17}O NMR spectrum corresponds to the added water. This signal is absent in the spectrum of the original (anhydrous) hydrogen peroxide solution (curve a in the insert).

^1H NMR of the same anhydrous and spiked solutions (as of Fig. 2) are depicted in Figure 3 (curves a and b, respectively). The spectra show the signals of ethyl acetate (1.6, 2.4, and 4.5 ppm) and a singlet of hydrogen peroxide at app. 9.8 ppm. Water signal is completely absent in the anhydrous solution, but after water spiking (to a level of 0.03:1 H_2O–H_2O_2) a broad water peak appeared at 4 ppm. The relative integral intensity of the peroxide signal was decreased after water addition due to proton exchange. The small, weak field shift (0.04 ppm) of the peroxide signal, after water addition, was due to the change in solvent composition.

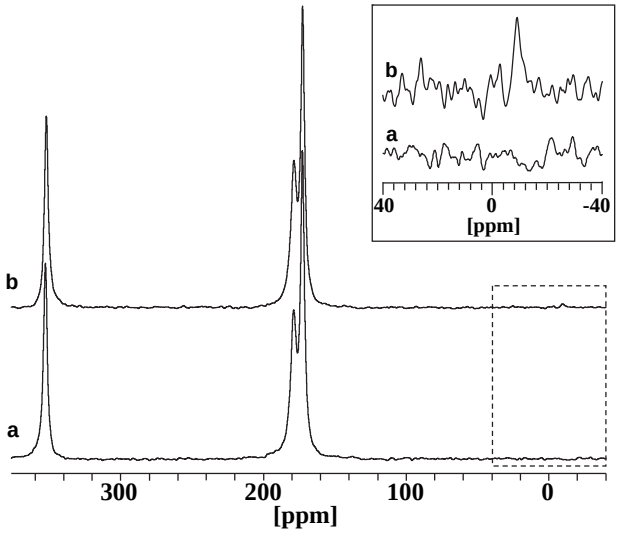

Figure 2. ^{17}O NMR spectra of anhydrous, 11% hydrogen peroxide-ethyl acetate solution, prepared from serine perhydrate before (curve a) and after (curve b) water addition. The insert presents a magnified spectra of the water region.

2.2. Preparation of pure hydrogen peroxide

Pure hydrogen peroxide was obtained by solvent evaporation from the anhydrous solution described above. Although it is possible to concentrate hydrogen peroxide from ethyl acetate solution, we preferred to purify the hydrogen peroxide from the somewhat more volatile methyl acetate. The solution was concentrated under vacuum, using oil an pump and liquid nitrogen trap. Hydrogen peroxide (99.4%) was obtained in 60% yield.

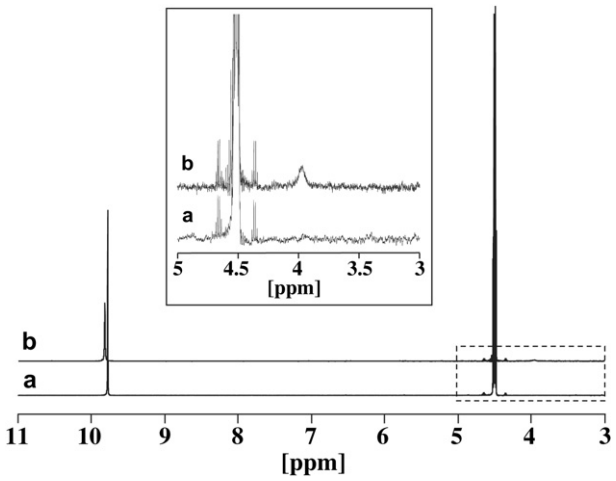

Figure 3. ^1H NMR spectra of anhydrous, 11% hydrogen peroxide-ethyl acetate solution prepared, from serine perhydrate before (curve a) and after (curve b) water addition. The insert presents magnified spectra of the water region.

3. Conclusions

We have outlined two related procedures based on serine perhydrate for the production of anhydrous, stabilizer-free hydrogen peroxide in organic solvents, and pure hydrogen peroxide. Both can be achieved by other protocols as well, but these procedures are simpler, and most importantly, they are much safer, and thus can be performed by most synthetic chemists. The procedures do not depend on the evaporation and heating of hydrogen peroxide, still they eliminate the stabilizer, and the ligating agent does not contaminate the product.

This protocol became possible only due to the crystallization of amino acid perhydrates. Because of their zwitterionic nature, serine and other amino acids are less soluble in most organic solvents, than all other existing hydrogen peroxide ligating agents (such as urea and DABCO), as well as hydrogen peroxide itself. An additional advantage of this procedure is its use in the formation of small quantities of anhydrous hydrogen peroxide solutions by microfluidic or other micro-devices. It is sufficient to pass a solvent over the crystalline amino acids perhydrate in order to obtain anhydrous hydrogen peroxide solution.

4. Experimental

4.1. Materials

Hydrogen peroxide (50%) was purchased from Aldrich–Sigma. Hydrogen peroxide (70%) was concentrated by vacuum evaporation from 50% hydrogen peroxide, at room temperature, using a nitrogen trap to collect the volatile fraction. It takes 1 h to accumulate 40 mL of product. L-serine, ethyl acetate, and methyl acetate were purchased from Sigma–Aldrich. Solvents were distilled over P_2O_5 before use.

CAUTION: Concentrated hydrogen peroxide is explosive.

Glassware for peroxide rich solutions: All glassware were treated by filling with 1 M NaOH for 1 day, then with 1 M nitric acid for an additional day, and finally with 10% hydrogen peroxide for an further day. Safety note: Sulfochromic acid or permanganate treatment should be avoided.

4.2. Instrumentation

X-ray powder diffraction measurements of the serine perhydrate starting material, and the residual crystals after

perhydrate decomposition, were performed on a D8 Advance diffractometer (Bruker AXS, Karlsruhe, Germany) with a goniometer radius of 217.5 mm, Göbel Mirror parallel-beam optics, 2° Sollers slits, and a 0.2 mm receiving slit. The powder samples were filled into low background quartz sample holders. The specimen weight was 0.5 g. XRD patterns in the range 2°–75° 2θ were recorded at room temperature using Cu Kα radiation (λ=1.5418 Å) under the following measurement conditions: Tube voltage of 40 kV, tube current of 40 mA, step scan mode with a step size 0.02° 2θ, and counting time of 1s/step. XRD patterns were processed by DiffracPlus software using Cambridge Structural Database.[20]

^{1}H and ^{17}O NMR spectra were collected on a Bruker Avance-500 (11.7483 T) spectrometer at resonance frequency of 500.2 and 67.8 MHz, respectively. The measurements were performed using a single pulse sequence with rf pulse duration of 10.9 and 8 μs, and recycling time of 7.34 s and 0.031 s for ^{1}H and ^{17}O NMR, respectively. Experiments were carried out at 25 °C. The ^{1}H and ^{17}O chemical shifts were measured relative to water.

The residual serine in the ethyl acetate and methyl acetate solutions was studied by Finnigan MAT HPLC system (P4000 pump, AS300 autosampler and UV6000LP detector), equipped with Alltech reversed phase C18, 5 μm, 250 mm length, and a 4.6 mm diameter column. We used 1:1 water–methanol eluant. The serine was first dansylated with dansyl chloride (Sigma–Aldrich) according to published procedure.[21] Quantification was conducted at 260 nm. Active oxygen content was determined by permanganatometry.[11]

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Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.tet.2010.04.109.

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