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Sonochemical dissolution of nanoscale ThO₂ and partial conversion into a Thorium Peroxo Sulfate

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Abstract

The influence of the sample morphology and experimental conditions towards the sonochemical dissolution of nanoscale ThO_2 samples in sulfuric acid media is described. Significant sonochemical dissolution rates and yields are observed at 20 kHz under Ar/O_2

- 15 atmosphere in dilute 0.5 M H_2SO_4 at room temperature, contrasting with the generallyreported high refractory behavior for ThO₂. The dissolution of ThO₂ combines the physical effects driven by acoustic cavitation phenomenon, the complexing affinity of Th(IV) in sulfuric medium and the sonochemical generation of H_2O_2 . These sonochemical conditions further allow the observation of the partial conversion of ThO₂ into a scarce Th(IV) peroxo
- 20 sulfate with 1D morphology resulting from one or both following processes: dissolution/reprecipitation or formation of an intermediate Th(IV) surface complex.

1. Introduction

- 25 Natural thorium-232 is a weakly radioactive element much more abundant than uranium on earth's crust. Potentially, thorium can be a key to developing a new generation of nuclear fuel for power stations [1,2]. Th-based fuels indeed allow to decrease the production of minor actinides during the burn-up and represent an interesting alternative for the reduction of the proportion of long-lived isotopes (transmutation of minor actinides) [3,4].
- 30 Thorium oxide is nevertheless a highly refractory material towards dissolution. The dissolution of ThO₂ in nitric acid solution is very low, particularly because no redox reaction is possible during the dissolution of this oxide [5]. The use of high-fired ThO₂-based fuel thus constitutes a serious problem in the nuclear fuel cycle in particular for the reprocessing step [6]. Several studies have reported that the addition of small amounts of hydrofluoric acid as
- 35 surface complexing agent in nitric aqueous solutions dramatically enhances the dissolution of thorium oxide [7–10]. Simonnet et al. proposed recently a dissolution mechanism for ThO₂ in HNO₃-HF mixture which takes into account the important effect of HF and the related formation of ThF₄ [11]. Other processing methods have been reported by changing the dissolution medium with CF₃SO₃H [12] or H₃PO₄ [13] for instance, or by using alternative
- 40 techniques such as pyrochemistry [14], autoclaves and microwaves [13,15]. Nevertheless, these methods are difficult to be applied in the current reprocessing processes because of safety requirements and due to the high corrosion of the equipment with fluoride ions.
- Nanosized thorium oxide may be suggested as a more reactive thorium-based fuel. Nanostructured materials can be defined as materials with a substructure of the order of a few nanometers (1-10 nm) [16,17]. These materials are of growing interest due to their attractive physical and chemical properties potentially optimized through their size,

morphology and structure [18,19]. The nanoscale particles or crystallites composing these materials have a large surface-to-volume ratio and provide a greater amount of active sites in comparison to bulk materials thus increasing their reactivity. In parallel, ThO₂ is largely studied because of its isomorphism with other tetravalent actinide oxides, its low solubility

- 5 in aqueous solutions and its good resistance to irradiation [20–22]. Particularly, Th(IV) crystallizes as oxide in the CaF₂ fluorite crystal system (Fm-3m space group) similarly with UO₂ and PuO₂. Furthermore, nanoscale actinide oxides are currently stirring up the curiosity of scientists due to their potential contribution in environmental migration of actinides and the safety considerations related to interactions with groundwater during storage of spent
- 10 nuclear fuel. Thorium, which only exists at the +IV oxidation state, therefore, offers the possibility of simulating the behavior of Pu-based oxide materials in less restrictive conditions without any contribution of redox processes (with however a difference in ionic radii for both elements: 1.05 Å against 0.96 Å for Th(IV) and Pu(IV), respectively, in 8-fold coordination [23]).
- 15

Sonochemistry appears as a suitable alternative for the dissolution of refractory materials and its efficiency towards dissolution has been reported with various refractory materials, including oxides such as ThO₂, PuO₂, CeO₂, etc. [24–26] The influence of sonication and HNO₃ concentration has, for instance, been discussed during the dissolution of uranium carbide in

- 20 nitric aqueous solutions [27]. In addition to the well-known physical effects driven by the acoustic cavitation, which generally dramatically enhance solid materials reactivity (e.g., surface erosion, particle fragmentation, mass transfer, etc.), the sonochemical in-situ generation of active species (H₂O₂, HO[°], HO₂[°], H₂, Ti³⁺, etc.) has been reported to significantly improve the dissolution of PuO₂ and CeO₂ in aqueous nitric acid solutions
- 25 [28,29]. More recently, a study highlighted the accumulation of intrinsic Pu(IV) colloids during the 20 kHz sonolysis of PuO₂ in pure water under Ar/(10%)CO atmosphere [30]. Moreover, it has been reported that sonochemistry can also induce the phase conversion of a solid. The topotactic conversion of chloroapatite into hydroxyapatite was for instance achieved by sonication of the former in deionized water (25°C) at 35 kHz [31]. In another
- 30 study, the transformation of anatase into rutile was observed during the synthesis of nanostructured TiO₂ via ultrasound assisted sol-gel technique [32]. This paper focuses on the sonochemical behavior of nanoscale ThO₂ powders in pure water and dilute aqueous solutions of H₂SO₄. H₂SO₄ has been selected because of its stability under ultrasound irradiation in combination to previous reports that demonstrated its significant effect
- 35 towards dissolution when compared to other conventional inorganic acids [33]. The reactivity of these materials is compared in terms of sonochemical effect towards dissolution and morphology evolutions. Particularly, the significant dissolution of ThO₂ and its partial conversion into a scarce Th peroxo sulfate is reported.

40 2. Experimental Section

Caution! ²³²Th is an α -emitting radioisotope and standard precautions should be followed for handling this chemical element.

2.1. Syntheses

45 All the used reagents were of analytical grade and were supplied by Sigma-Aldrich. The various aqueous solutions were prepared using deionized water (18.2 mΩ.cm at 25°C). Nanostructured thorium oxide samples exhibiting platelet morphology (n-STR) were

obtained by the conventional oxalic route [4,29,34]. Briefly, a 0.1 M thorium solution was prepared at room temperature by dissolving 3.239 g of Th(NO₃)₄.5H₂O in 50 mL of 1 M nitric acid solution before being slowly added to 53.89 mL of 0.5 M oxalic acid solution (previously prepared by dissolving 6.3 g of oxalic acid in 100 mL of 1 M nitric acid). One hour after

- 5 mixing the solutions (using a magnetic stir bar), Th(IV) oxalate precipitate was separated from the supernatant by centrifugation (9000 rpm during 5 min), washed twice with water and dried at room temperature under vacuum. The reference material (ThO₂ bulk) was obtained by firing Th(IV) oxalate precipitates (similar to nanostructured ThO₂) in air at 1000 °C during 2 h.
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Thorium oxide nanopowders (n-PWD) were obtained in basic conditions in the presence of a polymer at room temperature [35]. A 0.1 M thorium solution was prepared by dissolving 3.239 g of Th(NO₃)₄.5H₂O with 0.033 g of polyethylene glycol (PEG, M= 3000 g.mol⁻¹, 2.5 wt.%) in 50 mL of water. A solution of NH₄OH (30%) was slowly added to the thorium solution until the pH reached a value of 10 (about 3 mL). One hour after mixing the solutions (using a magnetic stir bar), Th(IV) hydroxide precipitate was separated from the supernatant by centrifugation (9000 rpm during 5 min), washed twice with water and dried at room temperature under vacuum. The different precursors (oxalate and ammonia routes) were then calcined under air at 485°C (during 2 h or 4 h) to obtain ThO₂ exhibiting different refractory behavior according to their nanoscale morphology (nanostructured, n-STR vs.

nanopowder, n-PWD) and particle size (crystallites) differences [36].

Table 1 summarizes the SEM, HR-TEM and S_{BET} characterizations performed on the ThO₂ samples. The nanostructuration (n-STR) of the oxides prepared by thermal conversion of oxalate precursors at 485°C is evidenced by HR-TEM with the observation of sintered nanoparticles (or crystallites) forming squared platelets. These nanoparticles are found to be monodispersed, quasi-spherical and crystalline, and measure about 7.6 ± 2.1 nm in diameter. Thorium oxide nanopowder (n-PWD), synthesized at 485°C from basic conditions, is also composed of agglomerates of spherical, monodispersed and crystalline nanoparticles

30 measuring about 7.7 ± 1.4 nm. These values contrast with the high sizes of the coherent domains already reported for ThO₂ calcined at high temperature (fired at 1000°C and used as a reference material in this study) but agree with a previous report evidencing the small crystallite sizes for low fired oxide precursors [36]. HR-TEM measurement of nanoparticle size are found to be consistent with values obtained from XRD (**Table 1**, Rietveld refinement)

35 thus confirming our observations and extracted values.

Table 1: ThO₂ sample characteristics and related nanoparticle sizes composing them and the sonolysis residues in different media (20 kHz, Ar/(20%)O₂, 20°C, 0.34 W.mL⁻¹) both determined by HR-TEM and XRD measurements (Rietveld refinement, when possible).

	Nanostructured ThO ₂ (n-STR)		ThO₂ nanopowder (n-PWD)		Reference material ThO ₂	
Synthesis route	oxalic route		basic route		oxalic route	
(conditions)	(485°C <i>,</i> 4 h)		(485°C, 2 h)		(1000°C, 2 h)	
SEM morphology	Squared platelets		Agglomerated NPs		Squared platelets	
S _{BET} (m ² .g ⁻¹)	13.5 ± 0.1		82.4 ± 0.1*		4.7 ± 0.1	
Particle size (nm)	HR-TEM	XRD	HR-TEM	XRD	HR-TEM	XRD
	7.6 ± 2.1	6.4 ± 0.7	7.7 ± 1.4	5.7 ± 0.1	66.6 ± 27.1	63.6 ± 1.5
Particle size for the sonolysis residue (nm)						

Water	8.8 ± 2.2	9.1 ± 0.9	7.0 ± 1.7	7.5 ± 1.1	-
0.05 M H ₂ SO ₄	7.6 ± 1.5	-	6.2 ± 1.2	-	-
0.5 M H ₂ SO ₄	7.9 ± 1.2	-	-	-	-

*value taken as an indicator from a previous report (ThO₂ n-PWD prepared at 450°C)[35]

2.2. Sonochemical experiments

- Two kinds of sonochemical reactors were used in this study, depending on the applied frequency. The experiments at low frequency ultrasound (20 kHz) were performed in a thermostated batch reactor containing 50 mL of solution with controlled saturating gas. Ultrasound was supplied with a 1 cm² titanium alloy probe fitted on top of the reactor and connected to a 750 W generator (Sonics & materials, Vibracell VCX 750) [37]. The experiments at high frequency ultrasound (345 kHz) were performed in a thermostated
- 10 cylindrical reactor (250 mL of solution) mounted on top of a 25 cm² high-frequency transducer (ELAC Nautik) and connected to a 125 W multifrequency generator. For high frequency experiments, an additional mechanical stirring fixed at 100 rpm was ensured by a glass blade to homogenize the suspensions and avoid formation of standing waves. For all of the experiments, the solution was sparged with Ar/(20%)O₂ about 20 min before sonication
- 15 and during the whole ultrasonic treatment at a controlled rate of 100 mL.min⁻¹. Some of the experiments have been performed in the presence of Ar/(10%)CO gas mixture. Carbon monoxide is known to be an effective scavenger of OH radicals leading to the inhibiting of H_2O_2 formation [38]. The temperature inside the reactor during the sonolysis was maintained at 20°C with a cryostat (Lauda Eco RE 1050) connected to the reactors. The
- 20 temperature was measured by a thermocouple immersed into the solution. The acoustic power density, P_{ac} (W.mL⁻¹), transmitted to the solution, was measured using the conventional thermal probe method [37] and reached 0.34 and 0.19 W.mL⁻¹ at 20 and 345 kHz, respectively. All the experiments were performed with the same quantity of thorium oxide powders (3.5 g.L⁻¹) that was suspended in different aqueous solutions (H₂O, 0.05 M
- 25 H₂SO₄, 0.5 M H₂SO₄). The sonolyses of the different solutions without any powder were considered as reference experiments.

2.3. Analyses and characterizations

- **UV-Vis absorption spectroscopy.** The sonochemical formation of H_2O_2 was followed by UV-30 Vis absorption spectroscopy. During sonolysis, aliquots of solutions (1 mL) were collected with a syringe through a septum and filtered with 0.2 µm PTFE filters (without any volume adjustment). Then, a small volume of the as-collected solution was mixed (1:1) with a 0.02 M Ti(IV) solution (previously prepared in 0.5 M H_2SO_4 by dissolution of TiOSO₄ salt) to form a yellow complex absorbing at 410 nm (ϵ = 722 cm⁻¹.M⁻¹). A calibration curve was previously
- 35 plotted with a commercial H_2O_2 solution previously titrated with a KMnO₄ solution. Absorption spectra were recorded in a 1 cm quartz cell from 280 to 800 nm using a Thermo Evolution 220 spectrophotometer. The statistical error for H_2O_2 formation rate was estimated to be lower than 10%.
- 40 Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES). The sonochemical dissolution of ThO₂ was followed by ICP-OES analysis with a Spectro Arcos apparatus (Spectro Analytical Instruments GmbH) equipped for axial plasma observation. A small volume of the collected solution aliquots (described above) was diluted with 0.3 M HNO₃ in the appropriate range of concentration prior to analysis. The concentration of thorium in solution was determined against an external calibration curve (0.1-15 mg L⁻¹) prepared with
- 45 solution was determined against an external calibration curve (0.1-15 mg.L⁻¹) prepared with

certified standard solutions of 1000 μ g.mL⁻¹ (SCP Science). The thorium content in solution was followed using several analytical wavelengths (401.913, 283.730, 274.716, 283.231 nm). The given value is a mean of three replicates. The statistical error for ThO₂ dissolution rate was estimated to be lower than 10%.

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 S_{BET} measurements. The specific surface area of ThO₂ samples (Table 1) was determined using nitrogen adsorption at 77 K after overnight degassing under vacuum at 573 K with a Micromeritics ASAP 2020 apparatus.

- 10 **Powder X-Ray Diffraction (PXRD).** PXRD diagrams were obtained with the use of a Bruker D8 Advance X-ray diffractometer equipped with a linear Lynx-eye detector (Cu K $\alpha_{1,2}$ radiation, λ = 1.54184 Å). PXRD patterns were recorded between 5° and 120° (θ -2 θ mode) at room temperature, with a step size of $\Delta(2\theta) = 0.02^\circ$ and a counting time of 1.8 s.step⁻¹. Powder X-Ray Diffraction (PXRD) confirmed the characteristic patterns of the fluorite structure (Fm-3m
- 15 space group) typical for ThO₂ for all of the studied samples in agreement with the literature and our previous report [36]. LaB₆ measurements were used to extract the instrumental functions. The collected data were refined by the Rietveld method when possible using the Fullprof_suite package [39].
- 20 **Raman spectroscopy.** Raman spectra were collected using a Horiba Jobin Yvon Aramis apparatus equipped with an edge filter and a Nd:YAG laser ($\lambda = 532$ nm). The laser beam was focused onto the sample simply deposited on a glass lamella (1 μ m²) with the use of an Olympus BX41 microscope. The spectra were recorded between 100 and 1500 cm⁻¹. Before the analysis of the sample, the apparatus was calibrated with a silicon wafer, using the first-order Si line at 520.7 cm⁻¹.

Scanning Electron Microscopy (SEM). The starting oxides and the solid residues obtained after sonolysis were characterized with SEM using a FEI Quanta 200 electron microscope. The samples were directly deposited onto carbon tapes without additional preparation.

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High-Resolution Transmission Electron Microscopy (HR-TEM). HR-TEM measurements were performed with a Jeol 2200 FS microscope (200 kV) equipped with a CCD GATAN USC camera. For HR-TEM analyses, sample aliquots were dispersed in absolute ethanol or pure water using an ultrasonic bath. One drop was then deposited onto a carbon-coated copper grid which was air-dried prior to analysis. For chemical analysis, the samples were characterized by Energy-Dispersive X-ray Spectroscopy (EDS) using a Silicon Drift Detector (SDD). Particle size measurements from HR-TEM analyses were determined by a statistical measurement using Image J software. The average value was given from at least 50 parallel measurements.

40

3. Results and Discussion

3.1. Effect of the different media on ThO₂ dissolution

The sonication of nanoscale ThO₂ powders (nanostructured ThO₂, n-STR, from oxalic route and ThO₂ nanopowder, n-PWD, from basic route) in aqueous solutions allows the observation of Th(IV) accumulation in solution as well as the formation of a solid residue at the end of the experiment (obtained by centrifugation and water washing of the sonicated mixture). Th(IV) accumulation kinetics are compared in **Figure 1** for the different aqueous systems. A comparable behavior can be noticed for both sonicated ThO₂ samples which are found highly resistant in pure water but significantly dissolve in sulfuric media. The dissolution rates and yields are furthermore found to significantly increase from 0.05 M H_2SO_4 to 0.5 M H_2SO_4 for ThO₂ n-STR. Higher yields (38% dissolved in 0.5 M H_2SO_4 in 900

- 5 min) are nevertheless observed for ThO₂ n-PWD which in addition exhibits practically zeroorder dissolution kinetics. The complexing affinity of sulfate-anion with Th(IV) cation has been reported to enhance the dissolution of ThO₂ with the formation of surface complexes at the solid/liquid interface [33]. The dissolution kinetics differences for both oxides can be related to their morphology and specific surface area. ThO₂ n-STR is indeed composed of
- 10 square platelets assembled from sintered particles whereas ThO₂ n-PWD is composed of small grain aggregates which facilitate its dissolution (increased surface availability). The induction period observed for the nanostructured sample (ThO₂ n-STR) at the beginning of its dissolution can be attributed to a first induction period related to platelets breaking and fragmentation which increase the available surface area and reactivity of the powder and 15 improve the dissolution rate of the oxide.



Figure 1: ThO₂ dissolution curves observed under 20 kHz ultrasound (20°C, Ar/(20%)O₂, 0.34 W.mL⁻¹) in pure H₂O, 0.05 M H₂SO₄ and 0.5 M H₂SO₄ for (a.) ThO₂ n-STR and (b.) ThO₂ n-PWD.

20 3.2. Sonication effect on ThO₂ dissolution

The effect of the ultrasonic wave and applied frequency on the dissolution rate of nanostructured ThO_2 and ThO_2 nanopowder in 0.05 M H_2SO_4 is illustrated on Figure 2. Whatever the oxide, mechanical agitation without ultrasound (silent conditions) does not lead to significant accumulation of Th after 480 minutes of treatment. Figure 2 also

- 25 demonstrates the significant effect of low frequency ultrasound for the dissolution of these refractory ThO₂ samples which usually requires the addition of fluoride ions in concentrated nitric acid medium [10]. A lower dissolution rate is indeed observed when applying high frequency ultrasound (345 kHz) in comparison to low frequency experiment (20 kHz). Generally, chemical effects have been reported to be favored at high frequency whereas 20
- 30 kHz ultrasound generates stronger physical effects expressed by surface erosion, particle fragmentations, decrease of diffusion layers, etc. As described above (see part 3.1.), this effect is clearly observable when comparing the sonochemical initial dissolution rates of nanostructured ThO₂ and ThO₂ nanopowder on **Figure 1**. Whereas Th accumulation rates is found linear when considering ThO₂ nanopowder, the ultrasound-assisted dissolution of
- 35 nanostructured ThO₂ indeed shows a time-increasing accumulation rate for Th (not linear)

evidencing an induction period at the first stage of dissolution. Such observation also explains that for similar conditions, higher yields are observed with n-PWD samples in comparison to n-STR (Figure 2.a. vs. 2.b.).



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Figure 2: Dissolution curves (Ar/(20%)O₂, 20°C) observed for (a.) ThO₂ n-STR and (b.) ThO₂ n-PWD suspended in 0.05 M H₂SO₄ at 20 kHz (0.34 W.mL⁻¹), 345 kHz (0.19 W.mL⁻¹) and in silent conditions.

3.3. Effect of the H_2O_2 formation on ThO₂ dissolution

- 10 The sonication of these samples in aqueous solutions (pure H₂O, 0.05 M H₂SO₄ and 0.5 M H₂SO₄) allowed to observe the accumulation of H₂O₂ which initial kinetics (W₀(H₂O₂)), measured in the presence or absence of ThO₂ powder, are represented in **Figure 3**. The kinetic values related to the initial H₂O₂ formation rates are gathered in **Table S1**, **ESI**. The higher formation rates observed at high frequency ultrasound (345 kHz) compared to low
- 15 frequency at 0.05 M H₂SO₄ are attributed to the dissociation of O₂ molecules in the cavitation bubble and the recombination of the generated radical products which increase H₂O₂ accumulation rates through various mechanisms [40–43]. In the studied experimental domain, the initial H₂O₂ formation rate shows a decreasing trend in the presence of ThO₂ powder whatever the medium or the applied acoustic frequency except for the experiment
- 20 carried out in 0.5 M H₂SO₄. Several hypotheses may explain the general tendency for H₂O₂ kinetics observed in the presence of oxide, including: (i) the complexation or catalytic decomposition of H₂O₂ on the surface of the oxide [35], (ii) the complexation reaction between H₂O₂ and dissolved Th(IV) [44–46], (iii) the redox or complexation reactions of H₂O₂ with Ti products resulting from the sonotrode erosion (only at 20 kHz), which is significantly
- 25 depassivated in sonicated sulfuric media. Probably, the discrepancies noted in 0.5 M H₂SO₄ regarding H₂O₂ accumulation rates can be partly attributed to interactions with Ti products. Note that a previous work reported a similar decrease in H₂O₂ formation rate in the presence of oxide powder related to a catalytic H₂O₂ decomposition [35]. Further work must be performed to explain the differences observed in the initial H₂O₂ formation in sulfuric acid media.



Figure 3: Representation of the initial H_2O_2 formation rates observed in the different sonicated media (Ar/(20%)O_2, 20°C) for ThO₂ n-STR and ThO₂ n-PWD calcined at 485°C at 20 kHz (0.34 W.mL⁻¹) or 345 kHz (0.19 W.mL⁻¹).

- 5 The effects of the saturating atmosphere (Ar/20%O₂, Ar/10%CO, Ar) and the addition of H_2O_2 on the sonochemical dissolution rate of ThO₂ n-STR at 20 kHz are illustrated in **Figure 4**. In 0.5 M H₂SO₄, the ultrasound-assisted dissolution rate of ThO₂ n-STR is much lower under Ar and Ar/CO than under Ar/O₂. In the presence of O₂, the formation rate of H_2O_2 is enhanced because of the scavenging of H radicals by O₂ [42,43]. Conversely, the presence of
- 10 CO, which reduces the dissolution rate, inhibits the accumulation of H_2O_2 similar to that observed in homogeneous aqueous solutions. In addition to the importance of the physical effects reported in part 3.2., these results confirm that the sonochemical generation of H_2O_2 significantly affect the dissolution of thorium oxide (**Figure 1**). This last assertion is confirmed with the observation of a significant increase of Th accumulation rate when adding hydrogen
- 15 peroxide ($[H_2O_2] = 0.01$ M) in the reactor during the 20 kHz sonication of nanostructured ThO₂ in 0.05 M H₂SO₄ (**Figure 4.b.**). It is interesting to note that these observations agree with previous investigations that demonstrated the significant effect of dilute hydrogen peroxide solutions for ThO₂ dissolution in comparison to conventional inorganic acids (in silent conditions).[33]



Figure 4: (a.) Sonochemical dissolution curves observed for nanostructured ThO₂ in 0.5 M H₂SO₄ at 20 kHz (20°C, 0.34 W.mL⁻¹) for the different atmosphere used. (b.) Sonochemical (20 kHz, Ar/(20%)O₂, 20°C, 0.34 W.mL⁻¹) dissolution curves for nanostructured ThO₂ suspended in 0.05 M H₂SO₄ without the addition of H₂O₂ and in the presence of 0.01 M H₂O₂ introduced in the reactor at t = 0 min.

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3.4. Characterization of the residual solid phase

SEM images acquired on the dissolution residues (obtained by centrifugation and pure water washing of the suspension mixture during sonolysis) generated in water during the treatment of the nanostructured sample (ThO₂ n-STR, oxalic route) confirm the progressive

- size reduction of the oxide platelets in agreement with the sonication time (Figure 5). This phenomenon is attributed to the physical effects driven by the collapsing acoustic bubbles (micro-jets, shock waves, particle collisions, etc.). The contrasting higher refractory behavior of reference ThO₂ calcined at 1000°C has been confirmed by studying its sonochemical reactivity in 0.5 M H₂SO₄ (Figure S1, ESI). For a similar platelet morphology, the resulting
- 15 dissolution rate is much lower than that observed for the nanoscale oxide calcined at 485 °C which agree with the generally-observed increased refractory behavior of high-fired oxides. This can be related to its lower specific surface area (Table 1) which results from the elimination of the porosity and crystal defects that occur when increasing the firing temperature or duration. Several studies already evidenced the relation between the
- 20 specific surface area of the oxide and its dissolution in acidic solutions [21,47]. Furthermore, a nanoscale effect often linked to the improved number of surface active sites, lattice stress, strains, etc. can also be proposed for the oxides fired at 485°C. It is important to remind that ThO₂ is known to be highly refractive towards dissolution, the here observed significant dissolution can be related to the nanoscale composition of the oxides made out of ca. 7 nm
- 25 nanoparticles. Previous studies already demonstrated that nanomaterials may offer significantly improved reactivity or physico-chemical properties [17,19,30,48]. Despite these important effects, the absence of dissolution for ThO₂ powders in pure H₂O as reported in Figure 1 (see part 3.1.), and inhibiting effect of CO (see Figure 4.a. in part 3.3.) indicate that the dissolution mechanism of ThO₂ does not result solely from the physical effects of the physical effects of the physical effects of the physical effects of the physical effects.
- 30 ultrasound but also depends on other parameters such as the complexing nature of the medium.



Figure 5: SEM images acquired on the starting nanostructured ThO₂ (485°C) and its corresponding sonolysis residue obtained in pure H₂O for different sonolysis times (20 kHz, Ar/(20%)O₂, 20°C, 0.34 W.mL⁻¹).

35 The effects of the acoustic cavitation on both nanoscale oxides sonicated in sulfuric acid medium are showed on the HR-TEM pictures obtained on the corresponding dissolution residues (**Figure 6**). Sonication of these oxides in dilute sulfuric acid solution leads to the strong platelets size reduction and fragmentation without significant modification of the crystallite size (see **Table 1**).



Figure 6: HR-TEM images of the starting nanostructured or nanopowdered ThO₂ samples and their corresponding sonolysis residues observed in 0.05 M H_2SO_4 (20 kHz, Ar/(20%)O₂, 20°C, 0.34 W.mL⁻¹).

- Raman spectra of the starting ThO₂ samples and corresponding sonolysis residues obtained in sulfuric medium are gathered in **Figure 7** and **Figure S2 (ESI)**. Both starting ThO₂ samples spectra are also compared to the one of the reference material ThO₂ calcined at 1000°C. An enlargement of the T_{2g} band located at 465 cm⁻¹ (FWHM) is observed with the decrease of the calcination temperature of ThO₂ samples. This phenomenon is a fingerprint for nanocrystals and can be explained by the confinement of optical phonons in nanosized
- 10 particles (crystallites) in agreement with the literature [49–53]. Further enlargement of the FWHM combined to a red shift of the T_{2g} band is clearly observed for the sonicated nanoscale ThO₂ sample residues. A similar observation has been made on nanostructured sample residues (ThO₂ n-STR) after sonication in pure water (**Figure S3, ESI**) evidencing that the observed peak features are not related to the dissolution progress itself. The
- 15 enlargement of the FWHM parameter is generally attributed to the shrinking particle size of oxide nanocrystals while the red shift is often correlated with the presence of defects, volume expansion, grain size distribution, etc. [49] The evolution of these two parameters for the T_{2g} band of the sonolysis residues cannot be explained by a particle size reduction since the size of the nanoparticles composing ThO₂ powders are found similar before and after sonication (Table 1 and Figure 6).
- 20 after sonication (Table 1 and Figure 6).



Figure 7: Normalized Raman spectra observed on reference material ThO₂ (1000°C), nanopowdered (n-PWD) ThO₂ (485°C) and its sonolysis residue obtained in 0.5 M H₂SO₄ (20 kHz, Ar/(20%)O₂, 20°C, 0.34 W.mL⁻¹). *artefact attributed to dust on the mirror of the spectrometer.

- 5 By contrast, the increased generation of strains, defects, and stress provided by the acoustic cavitation at the surface of the nanoparticles could significantly favor the interface reactivity involving a shift and enlargement of the T_{2g} band. Such effects influence the atomic surface configuration and its potential hydration and hydrolysis can be viewed as an additional surface stress that may influence these two processes. Particularly, surface hydrolysis
- 10 kinetics has been reported to exhibit significant geometry variation (in comparison to ThO₂) and strongly depend on the concentration and nature of surface defects [54,55]. In addition, the catalytic activity of many metal centers is known to be partly determined by the strength and amount of Lewis and Brønsted acid-base sites standing at the surface of the catalysts. ThO₂ exhibit catalytic properties (which are strengthened at the nanoscale) and ultrasonic treatment may increase the surface concentration of such meioties.
- 15 treatment may increase the surface concentration of such moieties.

3.5. Partial conversion of ThO₂ into a thorium peroxo sulfate

The sonolysis residues recovered after treatment of the nanoscale ThO₂ powders in different aqueous solutions were characterized by PXRD analysis (**Figure 8** and **Figure S4, ESI**). The 20 PXRD diagrams for the starting ThO₂ samples are gathered on **Figure S5, ESI**. The sonication residue diagrams for the nanoscale oxides display the characteristic patterns of the fluorite structure (Fm-3m space group) typical for ThO₂ (ICSD 01-071-6407). Some diffraction peaks corresponding to Ti (ICSD 00-044-1294) and attributed to the sonotrode erosion during the prolonged 20 kHz ultrasonic treatment, can also be observed. The PXRD diagrams of the

- 25 sonolysis residues obtained in sulfuric acid (0.05 M and 0.5 M) also show some additional diffraction peaks principally located at small angles that are not observed for the sonolysis residue obtained in pure water. These PXRD patterns correspond to a recently studied thorium peroxo sulfate, Th(O₂)(SO₄)(H₂O)₂, which crystallizes in the space group Pna2₁ of the orthorhombic system as evidenced by a combination of synchrotron PXRD and EXAFS
- 30 approaches [56]. In this compound, peroxo ligands coordinate Th centers in a scarce μ_{3} - $\eta^{2}:\eta^{2}:\eta^{2}$ bridging mode forming infinite 1D chains decorated with sulfato ligands. The corresponding purple PXRD diagram presented in **Figure 8** shows diffraction peaks matching with those observed at small angles for the sonolysis residues. This result indicates the partial conversion of both nanoscale ThO₂ samples into a thorium peroxo sulfate during

sonolysis. The low intensity of the diffraction peaks for this neoformed compound indicates its low proportion in the sample residue as well as its low crystallinity. This observation combined with the atomic form factor explains that the diffraction peaks at 2θ > 20° are poorly distinguishable. Furthermore, the crystallinity of the Th peroxo sulfate in silent conditions has been demonstrated to strongly depend upon the synthesis medium as evidenced in **Figure S6 (ESI)** which strengthens the observed low intensity of the diffraction peaks in the residue but also explains the better crystallinity noticed on XRD diagrams for this new compound in 0.05 M H₂SO₄ (in comparison to 0.5 M H₂SO₄).



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Figure 8: (a.) Normalized PXRD diagrams (background corrected) acquired on the sonolysis residues for nanostructured ThO₂ (485°C) treated in different media (20 kHz, Ar/(20%)O₂, 20°C, 0.34 W.mL⁻¹), and compared with the one of a thorium peroxo sulfate synthesized without ultrasound (purple spectrum).[56] Ticks stand for ICSD files for ThO₂ (ICSD 01-071-6407) and Ti (ICSD 00-044-1294). (b.) Magnification of the normalized PXRD diagram (background corrected) acquired on the sonolysis residue for nanostructured ThO₂ treated in 0.05 M H₂SO₄ (20 kHz, Ar/(20%)O₂, 20°C, 0.34 W.mL⁻¹), and compared with the one of a thorium peroxo sulfate synthesized without ultrasound.

Although high-frequency ultrasound generally enhance the sonochemical generation of H_2O_2 as expressed in **Figure 3** (see part 3.3.), the 345 kHz sonolysis of nanoscale ThO₂ in 0.05 M H_2SO_4 does not lead to the formation of Th peroxo sulfate species (**Figure S7, ESI**). This can be explained by the low dissolution of ThO₂ in these conditions (**Figure 2**, see part 3.2.) as a result of the absence of ThO₂ fragmentation and dispersion for such frequency. As it can be seen from PXRD data (**Figure S7, ESI**), a similar assessment can be mentioned in silent

- 25 conditions, whatever the considered oxide. Although evidenced by PXRD (Figure S4, ESI), the formation of thorium peroxo sulfate during the sonication of ThO₂ nanopowder in 0.05 M sulfuric acid is not obvious with SEM observation. Sample residue indeed shows a padded morphology with ill-defined small grain aggregates (Figure S8, ESI). By contrast, SEM characterizations confirmed the formation of this new crystalline phase in the dissolution
- 30 residue obtained after sonication of nanostructured ThO₂ (n-STR) in 0.05 M H₂SO₄ (Figure 9). A clear fragmentation and size reduction of the oxide platelets combined to the growth of a new phase forming fibers in agreement with the recently reported Th peroxo sulfate morphology [56], can be noted after 900 min of ultrasound. TEM experiments coupled with EDX spectroscopy consolidated the observation of the partial sonochemical conversion of
- 35 ThO₂ into thorium peroxo sulfate. Figure 10 shows a TEM image where a fiber particle is

observed close to small thorium oxide platelets. The EDX mapping confirmed the presence of thorium, oxygen and sulfur elements which support the formation of Th peroxo sulfate during the sonication of thorium oxide in sulfuric medium. The ThO₂ squared platelets also show thorium, oxygen and sulfur; the latter most probably resulting from the adsorption of sulfate on the surface of thorium oxide during sonolysis.



Figure 9: SEM images of nanostructured ThO₂ before (left) and after (right) sonication (20 kHz, Ar/(20%)O₂, 0.05 M H₂SO₄, 20°C, 0.34 W.mL⁻¹).



Figure 10: TEM images coupled with EDX mapping of the sonolysis residue obtained after 20 kHz sonication of nanostructured ThO₂ (485°C) in 0.05 M H_2SO_4 (Ar/(20%)O₂, 20°C, 0.34 W.mL⁻¹).

15 3.6. ThO₂ dissolution mechanism

The results described in the above discussion demonstrate that the significant dissolution of nanoscale ThO_2 samples observed in our conditions results from the physical (particle fragmentation and generation of defects) and chemical (generation of H₂O₂) effects driven by the 20 kHz acoustic cavitation phenomenon combined to an appropriate medium (sulfuric

20 media in this case). The various results that arose this conclusion are summarized in **Table 2** to help in the proposition of a relevant dissolution mechanism for nanoscale ThO₂ samples.

Usually, the dissolution of thorium oxide described in the literature involves a surface mechanism with ion adsorption on the surface sites of the oxide, chemical complexation reaction between the solid surface and the adsorbed species and finally, desorption of the thorium complex [11,47]. The formation of thorium peroxo sulfate during the sonolysis of ThO₂ in sulfuric acid solution can be interpreted by two different processes: (i) a solution

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coordination mechanism then precipitation, (ii) a surface complexation mechanism, or (iii) a combination of both processes.

Effect studied (fixed conditions)	Parameters	W₀(H₂O₂) (μM.min⁻¹)	Dissolution yield (%)	Thorium peroxo sulfate (x= yes)
Medium (20 kHz; Ar/O ₂)	H₂O	0.7	0	-
	0.05 M H ₂ SO ₄	3.2	3	Х
	0.5 M H ₂ SO ₄	1.6	20	Х
Ultrasonic frequency	20 kHz	3.2	3	Х
	345 kHz	20.5	1	-
(0.05 W1 112504, AT/ 02)	silent conditions	-	0.4	-
	Ar/CO	-	6	-
	Ar	0.9	7	Х
(0.5 IVI H2SO4, 20 KHZ)	Ar/O ₂	1.6	20	Х
Adding H2O2 (0.05 M H2SO4; 20 kHz; Ar/O2)	-	3.2	3	x
	[H ₂ O ₂] = 0.01 M	-	11	Х

Table 2: Summary of the different effects involved in ThO₂ n-STR dissolution.

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In the former case, a dissolution/reprecipitation process would involve the presence of Th(IV) in solution that could then be complexed with sulfate and generated H₂O₂ in agreement with the previous report described elsewhere [56]. In this case, the low precipitation kinetics already observed for this compound combined with the low amount of species available in solution (e.g., H₂O₂ consumption occurs through dissolution and catalytic decomposition at ThO₂ surface, see part 3.3.) would explain the low conversion yields (kinetics and solubility product). The absence of Th peroxo sulfate at high ultrasonic frequency and at silent conditions (see part 3.5.) favors this mechanism, so as the observation of fibers having very different morphology if compared with initial ThO₂ (**Figure**

15 **9**, see part 3.5.).

Alternatively, H₂O₂ and sulfate ligands can form surface complexes and facilitate the dissolution of ThO₂ in the form of Th(IV) peroxo and/or sulfate complexes. According to Table 2, the sonochemical generation of H₂O₂ is mandatory for ThO₂ dissolution. Most probably, H₂O₂ adsorption can occur by the replacement of H₂O molecules at ThO₂ surface as it was reported recently (Figure 11).[57] The effect of H₂SO₄ concentration could be assigned to the protonation of ThO₂ surface (initial steps described by the equations Eq. 1-2, the symbol ")))" stands for 20 kHz ultrasound irradiation) although the adsorption of sulfate cannot be excluded in agreement with the literature.[58] The formation of a mixed surface

25 complex could also be hypothesized. Nevertheless, the exact dissolution mechanism needs further investigations.

Surface hydrolysis and protonation:

 $= ThO_2 + H_2O \rightarrow))) \rightarrow = OTh(OH)_2$ (1) 30 $= OTh(OH)_2 + 2H^+ \rightarrow = OTh(OH_2^+)_2$ (2)

Note that mixtures of concentrated H₂O₂ and H₂SO₄ solutions are used reactants for the preparation of Caro's acid (peroxymonosulfuric acid). The formation of such strong oxidant acid remains however highly unlikely in our conditions due to the low amount of involved reactants and the high instability of peroxymonosulfuric acid. Furthermore, sonolytic

decomposition or splitting of sulfuric species are unlikely in these conditions. Previous studies indeed demonstrated the possible degradation of sulfuric media at much higher concentrations (> 9 M) when non-dissociated H₂SO₄ molecules predominate in solution and are able to enter the cavitation bubble which is not the case in our study.[59–61] Speciation diagram provided in **Figure S9 (ESI)** confirms that in our conditions (pH_{th}= 0.3 and 1.23 respectively in 0.5 and 0.05 M H₂SO₄), HSO₄⁻ is the predominant specie.



10 Figure 11: Scheme of the ultrasound-assisted dissolution of ThO₂.

4. Conclusion

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This study confirms the enhanced reactivity of nanoscale thorium oxides under ultrasound irradiation. Although being highly refractive towards dissolution in silent conditions, the

- 15 significant dissolution of ThO₂ can be achieved under 20 kHz sonication in dilute aqueous solutions of H₂SO₄. Dissolution rates and yields are strongly dependent upon (i) the physical effects driven by the acoustic cavitation such as the particle fragmentation or surface activation (strain, stress, hydrolysis, hydration, etc.), (ii) the sonochemical activity through the in-situ generation of hydrogen peroxide, and (iii) the complexing affinity of the medium
- 20 (sulfate) towards the oxide surface. The highest dissolution yields are observed with ThO₂ nanopowder sonicated at 20 kHz under Ar/(20%)O₂ atmosphere in 0.5 M H₂SO₄. Characterizations of the sonolysis residues with PXRD, SEM and HR-TEM revealed the partial conversion of ThO₂ into a scarce Th peroxo sulfate complex, which can be explained by one or both of the following mechanisms: dissolution/reprecipitation process and/or formation
- 25 of a surface activated complex. Further experiments are planned to clarify the dissolution mechanism and synthesize directly this compound under ultrasound with a thorium nitrate starting solution and with other counter-ions. In addition, the sonochemical reactivity of nanoscale PuO₂ in sulfuric acid solution will be studied while assuming the potential formation of an analogous Pu(IV) peroxo compound.
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