1.41
Sonochemistry

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1.41.1 INTRODUCTION

Ultrasonic irradiation of liquids causes high-energy chemical reactions to occur, often with the emission of light.[1–3] The origin of sonochemistry and sonoluminescence is acoustic cavitation: the formation, growth, and implosive collapse of bubbles in liquids irradiated with high-intensity sound. The collapse of bubbles caused by cavitation produces intense local heating and high pressures, with very short lifetimes. In clouds of cavitating bubbles, these hot-spots[4–6] have equivalent temperatures of roughly 5,000 K, pressures of about 1,000 atm, and heating and cooling rates above $10^{10}\,\mathrm{K\,s^{-1}}$. In single bubble cavitation, conditions may be even more extreme. Thus, cavitation can create extraordinary physical and chemical conditions in otherwise cold liquids.

When liquids that contain solids are irradiated with ultrasound, related phenomena can occur. When cavitation occurs near an extended solid surface, cavity collapse is non-spherical and drives high-speed jets of liquid into the surface.[7] These jets and associated shock waves can cause substantial surface damage and expose fresh, highly heated surfaces. Ultrasonic irradiation of liquid–powder suspensions produces another effect: high-velocity inter-particle collisions. Cavitation and the shockwaves it creates in a slurry can accelerate solid particles to high velocities.[8] The resultant collisions are capable of inducing dramatic changes in surface morphology, composition, and reactivity.[9]

Sonochemistry can be roughly divided into categories based on the nature of the cavitation event: homogeneous sonochemistry of liquids, heterogeneous sonochemistry of liquid–liquid or liquid–solid systems, and sonocatalysis (which overlaps the first two). In some cases, ultrasonic irradiation can increase reactivity by nearly a million-fold.[10] Because cavitation can only occur in liquids, chemical reactions are not generally seen in the ultrasonic irradiation of solids or solid–gas systems.

Sonoluminescence in general may be considered a special case of homogeneous sonochemistry; however, recent discoveries in this field have heightened interest in the phenomenon in and by itself.[11,12] Under conditions where an isolated, single bubble undergoes cavitation, recent studies on the duration of the sonoluminescence flash suggest that a shock wave may be created within the collapsing bubble, with the capacity to generate truly enormous temperatures and pressures within the gas.

1.41.1.1 Acoustic Cavitation

The chemical effects of ultrasound do not arise from a direct interaction with molecular species. Ultrasound spans the frequencies of roughly 15 kHz to 1 GHz. With sound velocities in liquids typically about 1,500 m s^{-1}, acoustic wavelengths range from roughly 10 cm to 10^{-4} cm. These are not molecular dimensions. Consequently, no direct coupling of the acoustic field with chemical species on a molecular level can account for sonochemistry or sonoluminescence.

Instead, sonochemistry and sonoluminescence derive principally from acoustic cavitation, which serves as an effective means of concentrating the diffuse energy of sound. Compression of a gas generates heat. When the compression of bubbles occurs during cavitation, it is more rapid than thermal transport, which generates a short-lived, localized hot-spot. Rayleigh's early descriptions of a mathematical model for the collapse of cavities in incompressible liquids predicted enormous local temperatures and pressures.[13] Ten years later, Richards and Loomis reported the first chemical and biological effects of ultrasound.[14]

If the acoustic pressure amplitude of a propagating acoustic wave is relatively large (greater than ≈0.5 MPa), local inhomogeneities in the liquid can give rise to the rapid growth of a nucleation site into a cavity of macroscopic dimensions, primarily filled with vapor. Such a bubble is inherently unstable, and its subsequent collapse can result in an enormous concentration of energy (Figure 1). This violent cavitation event is generally termed "transient cavitation." A normal consequence of this unstable growth and subsequent collapse is that the cavitation bubble itself is destroyed. Gas-filled remnants from the collapse, however, may give rise to reinitiation of the process.

A variety of devices have been used for ultrasonic irradiation of solutions. There are three general designs in use presently: the ultrasonic cleaning bath, the direct immersion ultrasonic horn, and flow reactors. The originating source of the ultrasound is generally a piezoceramic material that is subjected to a high AC voltage with an ultrasonic frequency (typically 15–50 kHz). The vibrating source is attached to the wall of a cleaning bath, to an amplifying horn, or to the outer surfaces of a flow-through tube or diaphragm. The ultrasonic cleaning bath is clearly the most accessible source of laboratory ultrasound and has been used successfully for a variety of liquid–solid heterogeneous sonochemical studies. The low intensity available in these devices (≈1 W cm^{-2}), however, means that even in the case of heterogeneous sonochemistry, an ultrasonic cleaning bath must be viewed as an apparatus of limited capability. The most intense and reliable source of ultrasound generally used in the chemical laboratory is the direct immersion ultrasonic horn (50 to 500 W cm^{-2}), as shown in Figure 2, which can be used for work under either inert or reactive atmospheres or at moderate pressures (<10 atm). These devices are available from several manufacturers at modest cost.

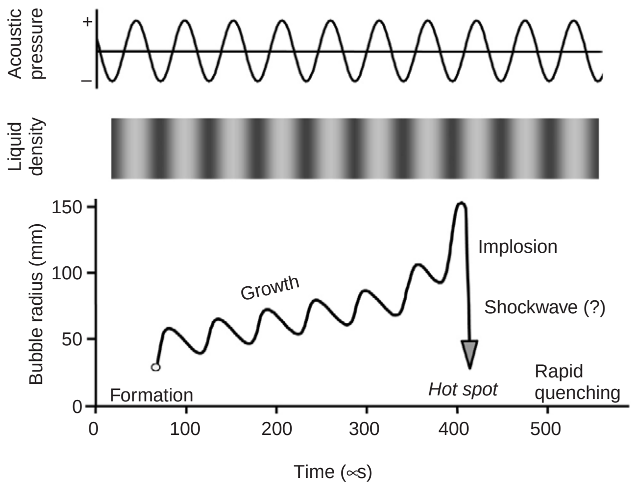


Figure 1 Transient acoustic cavitation: the origin of sonochemistry and sonoluminescence.

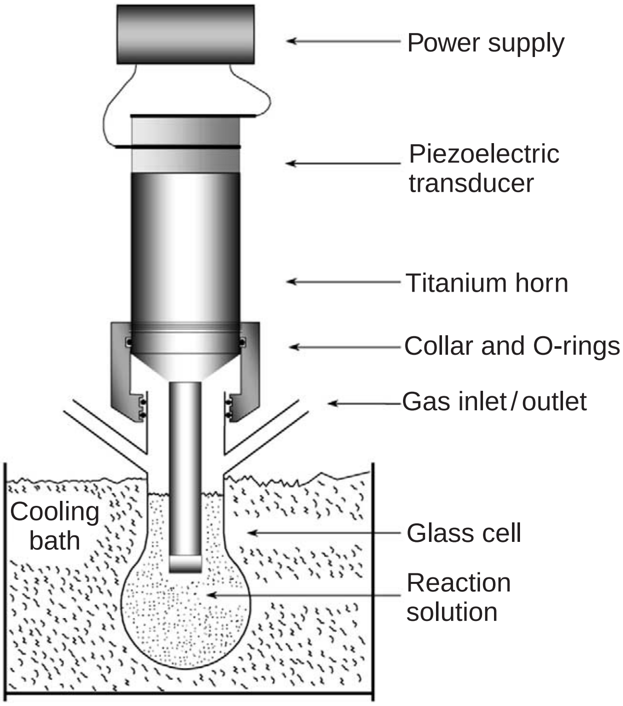


Figure 2 A typical sonochemical apparatus with direct immersion ultrasonic horn. Ultrasound can be easily introduced into a chemical reaction with good control of temperature and ambient atmosphere.

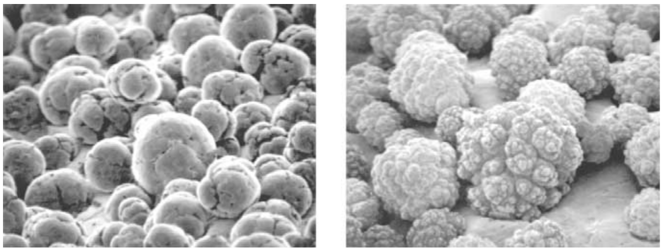
The generally accepted explanation for the origin of sonochemistry and sonoluminescence is the hot-spot theory, in which the potential energy given to the bubble as it expands to maximum size is concentrated into a heated gas core as the bubble implodes. The oscillations of a gas bubble driven by an acoustic field are well described by the "Rayleigh–Plesset" equation.[7]

The transient nature of the cavitation event precludes conventional examination of the conditions generated during bubble collapse. Chemical reactions themselves, however, can be used to probe reaction conditions through the use of "comparative-rate chemical thermometry."[4] These kinetic studies revealed that there were in fact *two* sonochemical reaction sites: the first (and dominant site) is the bubble's interior gas phase while the second is an *initially* liquid phase. The latter corresponds either to heating of a shell of liquid around the collapsing bubble or to droplets of liquid ejected into the hot-spot by surface wave distortions of the collapsing bubble.

1.41.1.2 Microjet Formation During Cavitation at Liquid–Solid Interfaces

A very different phenomenon arises when cavitation occurs near extended liquid–solid interfaces. There are two proposed mechanisms for the effects of cavitation near surfaces: microjet impact and shockwave damage. Whenever a cavitation bubble is produced near a boundary, the asymmetry of the liquid particle motion during cavity collapse induces a deformation in the cavity.[7] The potential energy of the expanded bubble is converted into kinetic energy of a liquid jet that extends through the bubble's interior and penetrates the opposite bubble wall. Because most of the available energy is transferred to the accelerating jet, rather than the bubble wall itself, this jet can reach velocities of hundreds of meters per second. Because of the induced asymmetry, the jet often impacts the local boundary and can deposit enormous energy densities at the site of impact. Such energy concentration can result in severe damage to the boundary surface. The second mechanism of cavitation-induced surface damage invokes shockwaves created by cavity collapse in the liquid. The impingement of microjets and shockwaves on the surface creates the localized erosion responsible for ultrasonic cleaning and many of the sonochemical effects on heterogeneous reactions. The erosion of metals by cavitation generates newly exposed, highly heated surfaces.

A solid surface several times larger than the resonance bubble size is necessary to induce distortions during bubble collapse. For ultrasound of $\approx$20 kHz, damage associated with jet formation cannot occur if the solid particles are smaller than $\approx$200 μm. In these cases, however,


before ultrasound

60 min. ultrasound

Figure 3 The effect of ultrasonic irradiation on the surface morphology and particle size of Ni powder. High-velocity interparticle collisions caused by ultrasonic irradiation of slurries are responsible for the smoothing and removal of passivating oxide coating. (reproduced with permission.[9])

the shockwaves created by homogeneous cavitation can create high-velocity interparticle collisions.[8,9] Suslick and co-workers have found that the turbulent flow and shockwaves produced by intense ultrasound can drive metal particles together at sufficiently high speeds to induce effective melting in direct collisions and the abrasion of surface crystallites in glancing impacts (Figure 3). A series of transition metal powders were used to probe the maximum temperatures and speeds reached during interparticle collisions. Using the irradiation of Cr, Mo, and W powders in decane at 20 kHz and 50 W cm^{-2}, agglomeration and essentially a localized melting occurs for the first two metals, but not the third. On the basis of the melting points of these metals, the effective transient temperature reached at the point of impact during interparticle collisions is roughly 3,000 °C (which is unrelated to the temperature inside the hot-spot of a collapsing bubble). From the volume of the melted region of impact, the amount of energy generated during collision was determined. From this, a lower estimate of the velocity of impact is roughly one half the speed of sound.[8] These are precisely the effects expected on suspended particulates from cavitation-induced shockwaves in the liquid.

1.41.2 SONOLUMINESCENCE

1.41.2.1 Types of Sonoluminescence

In addition to driving chemical reactions, ultrasonic irradiation of liquids can also produce light. Sonoluminescence was first observed from water in 1934 by Frenzel and Schultes.[15] As with sonochemistry, sonoluminescence derives from acoustic cavitation. It is now generally thought that there are two separate forms of sonoluminescence: multiple-bubble sonoluminescence (MBSL) and single-bubble sonoluminescence (SBSL).[11,12] Since cavitation is a nucleated process and liquids generally contain large numbers of particulates that serve as nuclei, the "cavitation field" generated by a propagating or standing acoustic wave typically consists of very large numbers of interacting bubbles, distributed over an extended region of the liquid. If this cavitation is sufficiently intense to produce sonoluminescence, then the phenomenon is MBSL.[1,16]

Under the appropriate conditions, the acoustic force on a bubble can be used to balance against its buoyancy, holding the bubble stable in the liquid by acoustic levitation. This permits examination of the dynamic characteristics of the bubble in considerable detail, from both a theoretical and an experimental perspective. Such a bubble is typically quite small compared to an acoustic wavelength (e.g., at 20 kHz, the resonance size is approximately 150 μm). For rather specialized but easily obtainable conditions, a single, stable, oscillating gas bubble can be forced into such large-amplitude pulsations that it produces sonoluminescence emissions on each (and every) acoustic cycle. Such SBSL is outside the scope of this chapter.

1.41.2.2 Spectroscopic Probes of Cavitation Conditions

The MBSL of both aqueous and non-aqueous solutions is similar to the emission expected from high-temperature flames; e.g., excited-state $OH^{\cdot}$ from water, excited states of C_2 ($d^3\Pi_g - a^3\Pi_u$,) from hydrocarbons (these lines also give hydrocarbon flames their blue color), and CN excited states in the presence of a nitrogen source. For both aqueous and non-aqueous liquids, MBSL is caused by chemical reactions of high-energy species formed during cavitation by bubble collapse. Its principal source is most probably not blackbody radiation or electrical discharge. MBSL is a form of chemiluminescence.[16]

Determination of the temperatures reached in a cavitating bubble has remained a difficult experimental problem. As a spectroscopic probe of the cavitation event, MBSL provides a solution. High-resolution MBSL spectra from silicone oil under Ar have been reported and analyzed.[5] The observed emission comes from excited-state C_2 and has been modeled with synthetic spectra as a function of rotational and vibrational temperatures. From comparison of synthetic to observed spectra, the effective cavitation temperature is 5,050 ± 150 K.

A second spectroscopic thermometer comes from the relative intensities of atomic emission lines in the sonoluminescence spectra of excited-state metal atoms produced by sonolysis of volatile Fe, Cr, and Mo carbonyls. Sufficient spectral information about emissivities of many metal atom excited states are available to readily calculate emission spectra as a function of temperature. Because of this, the emission spectra of metal atoms are extensively used by astronomers to monitor the surface temperature of stars. From comparison of calculated spectra and the observed MBSL spectra from metal carbonyls, another measurement of the cavitation temperature was obtained.[6] The effective emission temperature from metal atom emission during cavitation under argon at 20 kHz is 4,900 ± 250 K.

The excellence of the match between the observed MBSL and the synthetic spectra provides definitive proof that the sonoluminescence event is a thermal, chemiluminescence process. The agreement among these spectroscopic determinations[5,6] of the cavitation temperature and to that made by comparative rate thermometry of sonochemical reactions[4] is extremely good.

1.41.3 SONOCHEMISTRY

In a fundamental sense, chemistry is the interaction of energy and matter. Chemical reactions require energy in one form or another to proceed: chemistry stops as the temperature approaches absolute zero. One has only limited control, however, over the nature of this interaction. In large part, the properties of a specific energy source determine the course of a chemical reaction. Ultrasonic irradiation differs from traditional energy sources (such as heat, light, or ionizing radiation) in duration, pressure, and energy per molecule. The immense local temperatures and pressures and the extraordinary heating and cooling rates generated by cavitation bubble collapse mean that ultrasound provides an unusual mechanism for generating high-energy chemistry. Like photochemistry, very large amounts of energy are introduced in a short period of time, but it is thermal, not electronic, excitation. As in flash pyrolysis, high thermal temperatures are reached, but the duration is very much shorter (by $>10^4$) and the temperatures are even higher (by five- to tenfold). Similar to shock-tube chemistry or multiphoton infrared laser photolysis, cavitation heating is very short lived, but occurs within condensed phases. Furthermore, sonochemistry has a high-pressure component, which suggests that one might be able to produce on a microscopic scale the same macroscopic conditions of high-temperature pressure "bomb" reactions or explosive shockwave synthesis in solids. Control of sonochemical reactions is subject to the same limitation that any thermal process has: the Boltzmann energy distribution means that the energy per individual molecule will vary widely. One does have easy control, however, over the intensity of heating generated by acoustic cavitation using various physical parameters (including thermal conductivity of dissolved gases, solvent vapor pressure inside the bubble, and ambient pressure). In contrast, frequency appears to be less important, at least within the range where cavitation can occur (a few hertz to a few megahertz), although there have been few detailed studies of its role.

1.41.3.1 Homogeneous Sonochemistry: Bond Breaking and Radical Formation

The chemical effects of ultrasound on aqueous solutions have been studied for many years. The primary products are H_2 and H_2O_2; there is strong evidence for various high-energy intermediates, including HO_2, $H^{\cdot}$, $OH^{\cdot}$.[17] As one would expect, the sonolysis of water, which produces both strong reductants and oxidants, is capable of causing secondary oxidation and reduction reactions, as often observed by Margulis and co-workers.[18] Most recently there has been strong interest shown in the use of ultrasound for remediation of low levels of organic contamination of water.[19] The $OH^{\cdot}$ radicals produced from the sonolysis of water are able to attack essentially all organic compounds (including halocarbons, pesticides, and nitroaromatics) and through a series of reactions oxidize them fully. The ultrasonic irradiation of organic liquids creates the same kinds of products associated with very-high-temperature pyrolysis.[20] The sonochemistry of solutes dissolved in organic liquids also remains largely unexplored. The sonochemistry of metal carbonyl compounds is an exception.[21] Detailed studies of these systems led to important mechanistic understandings of the nature of sonochemistry. A variety of unusual reactivity patterns have been observed during ultrasonic irradiation, including multiple ligand dissociation, novel metal cluster formation, and the initiation of homogeneous catalysis at low ambient temperature.[21]

1.41.3.2 Applications of Sonochemistry to Materials Synthesis

Of special interest is the recent development of sonochemistry as a synthetic tool for the creation of unusual inorganic materials.[22] As one example, the recent discovery of a simple sonochemical synthesis of amorphous iron helped settle the long-standing controversy over its magnetic properties.[23,24] More generally, ultrasound has proved extremely useful in the synthesis of a wide range of nanostructured materials, including high-surface-area transition metals, alloys, carbides, oxides, and colloids.[22,25–27] Sonochemical decomposition of volatile organometallic precursors in high-boiling solvents produces nanostructured materials in various forms with high catalytic activities. Nanometer colloids; nanoporous high-surface-area aggregates; nanostructured carbides, sulfides, and oxides; and supported heterogeneous catalysts can all be prepared by this general route, as shown schematically in Figure 4. As an example, ultrasonic irradiation of $Mo(CO)_6$ produces aggregates of nanometer-sized clusters of face-centered cubic molybdenum carbide, with high porosity and very large surface area. The catalytic properties showed that the molybdenum carbide generated by ultrasound is an active and highly selective dehydrogenation catalyst comparable to commercial ultrafine platinum powder.[25] In related work, Gedanken and co-workers have extended the sonochemical synthesis of amorphous transition metals to the production of nanostructured metal oxides simply by sonication in the presence of air.[26–28]

The sonochemical synthesis of nanostructured molybdenum sulfide[29] provides another example of the utility of sonochemistry to the production of active catalysts. MoS_2 is the predominant hydrodesulfurization catalyst heavily used by the petroleum industry to remove sulfur from fossil fuels before combustion. The sonochemical synthesis of MoS_2 by the irradiation of solutions of molybdenum hexacarbonyl generates a most unusual morphology. As shown in Figure 5, conventional MoS_2 shows a plate-like morphology typical for such layered materials, whereas the sonochemical MoS_2 exists as a porous agglomeration of clusters of spherical particles with an average diameter of 15 nm. Despite the morphological difference between the sonochemical and conventional MoS_2, TEM images of both sulfides show lattice fringes with interlayer spacings of 0.62 ± 0.01 nm. The sonochemically prepared MoS_2, however, shows much greater edge and

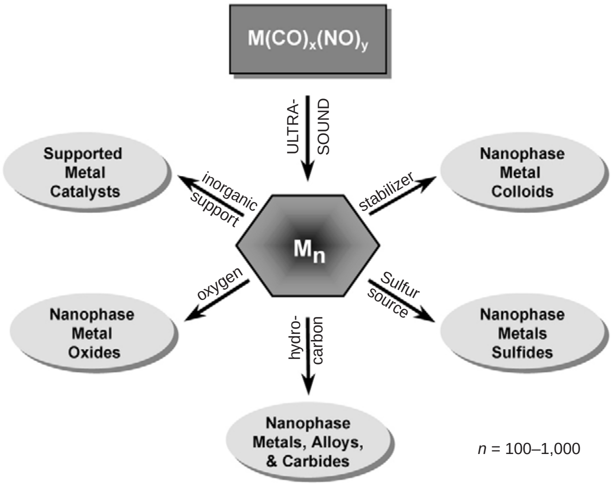


Figure 4 Sonochemical synthesis of nanostructured inorganic materials.

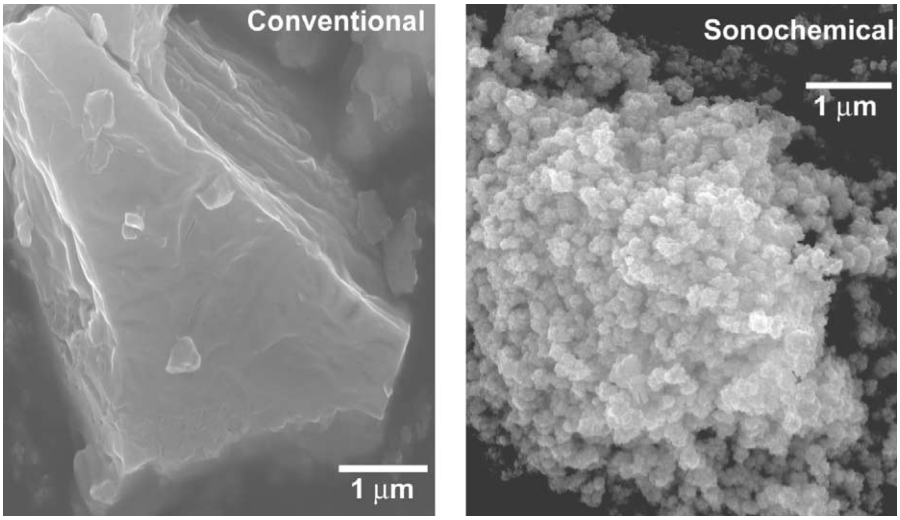


Figure 5 Morphology of conventional and sonochemically prepared MoS_2.

defect content, as the layers must bend, break, or otherwise distort to form the outer surface. It is well established that the activity of MoS_2 is localized at the edges and not on the flat basal planes. Given the inherently higher edge concentrations in nanostructured materials, the catalytic properties of sonochemically prepared MoS_2 shows substantially increased activity for hydrodesulfurization.

Using a very different route, Grieser and co-workers have sonochemically produced nanocrystalline CdS colloids.[30] *In situ*-generated hydrogen sulfide from the sonication of 2-mercaptopropionic acid acted as the sulfiding agent. Spectroscopic studies revealed that sonication produces CdS particles in the quantum dot range ("Q-state", ~3 nm diameter in this study) and the sonication time and the thiol type determine the particle size distribution.

1.41.3.3 Heterogeneous Sonochemistry: Reactions of Solids with Liquids

The use of ultrasound to accelerate chemical reactions in heterogeneous systems has become increasingly widespread. The physical phenomena that are responsible include the creation of emulsions at liquid–liquid interfaces, the generation of cavitational erosion and cleaning at liquid–solid interfaces, the production of shockwave damage and deformation of solid surfaces, the enhancement in surface area from fragmentation of friable solids, and the improvement of mass transport from turbulent mixing and acoustic streaming.

The use of high-intensity ultrasound to enhance the reactivity of metal powders and surfaces as stoichiometric reagents has become an especially routine synthetic technique for many heterogeneous organic and organometallic reactions,[1–3] particularly those involving reactive metals such as Mg, Li, or Zn. This development originated from the early work of Renaud and the more recent breakthroughs of Luche.[3] The effects are quite general and apply to reactive inorganic salts and to main group reagents as well. Less work has been done with unreactive metals (e.g., V, Nb, Mo, W), but results here are promising as well. Rate enhancements of more than 10-fold are common, yields are often substantially improved, and by-products avoided. A range of synthetically useful examples of heterogeneous sonochemical reactions are listed in Table 1.

The mechanism of the sonochemical rate enhancements in both stoichiometric and catalytic reactions of metals is associated with dramatic changes in morphology of both large extended surfaces and of powders. As discussed earlier, these changes originate from microjet impact on large surfaces and high-velocity interparticle collisions in slurries. Surface composition studies by Auger electron spectroscopy and sputtered neutral mass spectrometry reveal that ultrasonic irradiation effectively removes surface oxide and other contaminating coatings.[9] The removal of such passivating coatings can dramatically improve reaction rates. The reactivity of clean metal surfaces also appears to be responsible for the greater tendency for heterogeneous sonochemical reactions to involve single electron transfer rather than acid-base chemistry.[31]

Significant applications of sonochemistry to heterogeneous catalysis have also been noted.[32] Among the more impressive results are hydrogenations and hydrosilations by Ni powder, Raney

Table 1 Some representative examples of heterogeneous sonochemistry.

Heterogeneous reagent	*Reactant*	*Products*
Compounds of metals		
$LiAlH_4$	Ar-X	ArH
$LiAlH_4$	R_3M-X (X = Cl, NR_2,OR)	R_3M-H (M = Si,Ge,Sn)
Al_2O_3	$C_6H_5CH_2Br + KCN$	$C_6H_5CH_2CN$
$KMnO_4$	$RR'HCOH$	$RR'CO$
CrO_2Cl_2	$RR'HCOH$	$RR'CO$
HBR_2	$R'_2C{=}CR'_2$	$HR'_2C\text{-}CR'_2(BR_2)$
MS_2, V_2O_5	NR_3, py, Cp_2Co	Intercalates
Hg		
	$(HR_2BrC)_2CO + R'CO_2H$	$(HR_2C)CO(C(O_2CR')R_2)$
	$(HR_2BrC)_2CO + R'OH$	$(HR_2C)CO(C(OR')R_2)$
Mg		
	R-Br	R-MgBr
	$R_2C{=}CHCH_2Cl + Mg/C_{14}H_{14}$	$R_2C{=}CHCH_2MgCl$
Li		
	R-Br (R = Pr, n-Bu, Ph)	R-Li
	$R\text{-}Br + R'R''CO$	$RR'R''COH$
	$R\text{-}Br + (H_3C)_2NCHO$	RCHO
	R_3M-Cl (M = C,Si,Sn)	R_3MMR_3
	R_2SiCl_2 (R = arenes)	cyclo-$(R_2Si)_3$
	$R_2MCl_2 + Na + Se$ (M = Si,Sn)	$(R_2MSe)_3$
Zn		
	$CF_3I + RR'C{=}O$	$RR'C(OH)CF_3$
	$C_nF_{2n+1}I + CO_2$	$C_nF_{2n+1}CO_2H$
	$RR'C{=}O + BrCH_2CO_2R''$	$RR'C(OH)CH_2CO_2R''$
	$PhBr + RCOCH{=}CHR' + Ni(acac)_2$	$RCOCH_2CHR'Ph$ (R = H,alkyl)
	$RR'C{=}O + R''_2C{=}CHCH_2Br$	$RR'(HO)CCR''_2CH{=}CH_2$
Transition metals		
	$MCl_5 + Na + CO$ (M = V,Nb,Ta)	$M(CO)_6^-$
	$MCl_6 + Na + CO$ (M = Cr,Mo,W)	$M_2(CO)_{10}^{-2}$
	$MnCl_3 + Na + CO$	$Mn(CO)_5^-$
	$FeCl_3 + Na + CO$	$Fe(CO)_4^{-2} + Fe_2(CO)_8^{-2}$
	$Fe_2(CO)_9$ + alkenylepoxide	$Fe(CO)_3(\pi$-allyllactone)
	$Fe_2(CO)_9 + RHC{=}CR'\text{-}CH{=}CHR'$	$Fe(CO)_3(\eta^4$-diene)
	$NiCl_2 + Na + CO$	$Ni_6(CO)_{12}^{-2}$
	$NiCl_2$ + Na + bipy + COD/CDT	Ni(bipy)(COD/CDT)
	$Co(acac)_3 + C_5H_6 + COD + Mg/C_{14}H_{10}$	Co(Cp)(COD)
	$RuCl_3$ + Li + 1,5-cyclooctadiene	$(\eta^6$-1,3,5-COT)$(\eta^4$-1,5-COD)Ru(0)
	$[Fe(C_5R_5)(CO)_2]_2 + K + Ph_3C^+$	$Fe(C_5R_5)(CO)_2(C_2H_4)^+$
	$[M(C_5R_5)(CO)_n]_2$ + K(M = Fe,Ru,Mo)	$[M(C_5R_5)(CO)_n]^-$
	$Pd + CH_2{=}CHCH_2X$	$[(\eta^3\text{-}H_2C\text{-}CH\text{-}CH_2)Pd(X)]_2$
	$La + NH_4SCN$ in HMPA	$La(NCS)_3 \cdot 4HMPA$
	Cu + *o*-$C_6H_4(NO_2)I$	*o*-$(O_2N)H_4C_6\text{–}C_6H_4(NO_2)$

Ni, and Pd or Pt on carbon. For example, the hydrogenation of alkenes by Ni powder is enormously enhanced ($>10^5$-fold) by ultrasonic irradiation.[10] This dramatic increase in catalytic activity is due to the formation of uncontaminated metal surfaces from interparticle collisions caused by cavitation-induced shockwaves.

1.41.4 CONCLUSIONS

Since the early 1980s, sonochemistry has become a well-defined technique for both mechanistic and synthetic studies. The general details of the process of acoustic cavitation and the high-energy chemistry generated during such bubble collapse are now reasonably well understood. The major challenges that face a wider application of this technology include issues of scale-up and energy efficiency. While laboratory equipment for sonochemical reactors are readily available commercially, larger-scale apparatus is only now becoming commercially available. Perhaps more importantly, sonochemistry shares with photochemistry an energy inefficiency that remains problematic: while the production of ultrasound from electrical power can be extremely efficient, the coupling of ultrasound into chemically useful cavitation events remains a low-yield event. As we begin to understand the physics of cavitation clouds and dense multiphase acoustics, more effective means of inducing cavitation in liquids may alleviate this current limitation.

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