New sonochemiluminescence involving solvated electron in Ce(III)/Ce(IV) solutions

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ABSTRACT

The moving single-bubble sonoluminescence of Ce³⁺ in water and ethylene glycol solutions of CeCl₃ and (NH₄)₂Ce(NO₃)₆ was studied. As found, a significant part of intensity of the luminescence (100% with cerium concentration less than 10⁻⁴ M) is due to the sonochemiluminescence. A key reaction of sonochemiluminescence is the Ce⁴⁺ reduction by a solvated (or hydrated in water) electron: Ce⁴⁺ + eₛ (eₐq) → *Ce³⁺. Solvated electrons are formed in a solution via electrons ejection from a low-temperature plasma periodically generated in deformable moving bubble at acoustic vibrations. Reactions of heterolytic dissociation of solvents make up the source of electrons in the plasma. In aqueous CeCl₃ solutions, the Ce⁴⁺ ion is formed at the oxidation of Ce³⁺ by OH radical. The latter species originates from homolytic dissociation of water in the plasma of the bubble, also penetrating from the moving bubble into the solution. The sonochemiluminescence in cerium trichloride solutions are quenched by the Br⁻ (acceptor of OH) and H⁺ ions (acceptor of eₐq). In water and ethylene glycol solutions of (NH₄)₂Ce(NO₃)₆, the sonochemiluminescence also quenched by the H⁺ ion. The sonochemiluminescence in CeCl₃ solutions is registered at [Ce³⁺] ≥ 10⁻⁵ M. Then the sonochemiluminescence intensity increases with the cerium ion concentration and reaches the saturation plateau at 10⁻² M. It was shown that sonophotoluminescence (re-emission of light of bubble plasma emitters by cerium ions) also contributes to the luminescence of Ce³⁺ in solutions with [Ce³⁺] ≥ 10⁻⁴ M. If the cerium concentration is more than 10⁻² M, a third source contributes to luminescence, viz., the collisional excitation of Ce³⁺ ions penetrating into the moving bubble.

1. Introduction

Sonochemiluminescence (SCL) is one of the types of light radiation during ultrasonic irradiation of solutions [1] in addition to sonoluminescence (SL) associated with emitting photons by cavitation bubbles [2]. SCL occurs in the reactions of products that arise and enter the solution during the decomposition of low-temperature plasma. The latter is periodically generated in the bubbles from the compounds of the solution during the acoustic vibrations [3]. Such SCL is known for many systems, e.g. aqueous solutions of luminol [3], acridinium NHS ester [4], chelated Tb³⁺, Ru(bpy)₂²⁺, Ru(bpy)₃³⁺ complexes [5–7] and non-aqueous solutions of various organic compounds [8–10]. Among them, a particular attention is paid to the systems whereby chemiluminescence (CL) arises in the reactions involving the sonolytically generated solvated electron (eₛ). This reagent has an unusually high reducing ability. Therefore, exothermic redox reactions with its participation usually results in the electronically excited products. For example, in aqueous solutions of ruthenium(III)-bipyridyl complex, the excited MLCT state of the Ru(bpy)₃²⁺ (Ru(bpy)₃³⁺) emerges directly in the elementary act of reduction upon transferring electron to the ligand-centered orbital unoccupied in the initial Ru(bpy)₃³⁺ complex. This luminescent reaction confirmed the electron ejection from the plasma of the bubble and previously unknown generation of the hydrated (or solvated, in a general case) electron (eₐq) during moving single-bubble sonolysis of water (1):

H₂O → H₂O + e → eₐq

besides the processes involving other primary products of the sonolysis (2) [7]:

H₂O → H⁺ + OH

Obviously, similar reactions can also occur during sonolysis of other substances whereby their reduction with the hydrated (or solvated, in a general case) electron generates the electronically excited emitters. This

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should expand the list of SCL systems.

Based on this hypothesis, this work aims searching for SCL associated with the reduction of the Ce$^{4+}$ ions during moving single-bubble sonolysis of the Ce$^{4+}$ and Ce$^{3+}$ solutions in water and ethylene glycol (Ce$^{4+}$ is formed during the sonolysis from Ce$^{3+}$). The choice of cerium compounds for this purpose is due to the high exothermicity of the Ce$^{4+}$ reduction with $e_{eq}$ (and probably of Ce$^{4+}$ with $e_1$ in ethylene glycol) and possible formation of excited ion $^*\text{Ce}^{3+}$, which has a high quantum yield of photoluminescence (PL) in water. Note that the formation of $^*\text{Ce}^{3+}$ has not been previously detected despite the above considerations and numerous studies on reduction process Ce$^{4+}$ $\rightarrow$ Ce$^{3+}$ during sonolysis and radiolysis [11,12].

2. Experimental part

The bidistilled water was used for the preparations of the solutions; ethylene glycol and sulfuric acid of a high degree of purity were additionally distilled. Salts CeCl$_3$$\cdot$7H$_2$O, (NH$_4$)$_2$Ce(NO$_3$)$_6$, and KBr of a high-purity grade were from Sigma-Aldrich and used without further purification. The single-bubble sonolysis of the solutions was performed in a spherical glass flask resonator with the piezoelectric transducers oppositely glued (volume ~ 100 mL, resonant frequency ~ 26 kHz). To avoid the reaction of $e_1$ with dissolved oxygen all the solutions were prepared with evacuation at 0.01 Torr for 30–40 min to remove the dissolved gases and further saturation with argon by bubbling the gas through the solution (flow rate 5 mL·s$^{-1}$, 5–6 min). Then the solutions were additionally evacuated for 30 min. This procedure is also necessary to obtain reproducible and bright single-bubble sonoluminescence (SBSL).

The sonoluminescence spectra and concentration dependences of SL intensity were registered with spectrofluorimeter Aminco Bowman (Hamamatsu R3896 photomultiplier, $\Delta\lambda=2$ nm). The photon emission from the cavitation bubble in the center of the flask was delivered to the entrance slit of the spectrofluorimeter using the quartz fiber (the diameter is 0.4 mm). Its starting point was located in 5 mm from the bubble. The relative spectral sensitivity of the detection system was determined using a lamps with a known spectral distribution of its radiation intensity: DDS-30 deuterium lamp in the range of 250–400 nm and KGM-650 tungsten halogen lamp at 350–600 nm. When recording SBSL, the temperature was maintained in the range of 2–5 °C. The acoustic pressure ($p_a$) in the middle of the resonator flask was measured with hydrophone 8103 Bruel & Kjaer. Ultrasonic treatment was carried out only when spectra are recording (about 1.5 min). To obtain the averaged spectra the treatment of one solution was carried out 3 times, but no more, after which fresh solutions were prepared. The final spectra were obtained by averaging 10 experimental spectra. PL and absorption spectra were recorded respectively with spectrofluorimeter Fluorolog-3 Horiba Jobin Ivon and spectrophotometer Shimadzu UV-1800. The photographs of SBSL were taken with camera Nikon 3000D.

3. Results and discussion

3.1. Luminescence of $^*\text{Ce}^{3+}$ during sonolysis of CeCl$_3$ solutions in water

Fig. 1 shows the spectra of the single-bubble sonoluminescence of water and CeCl$_3$ aqueous solutions with different concentrations at the acoustic pressure of 1.16–1.32 bar. When the latter equals 1.2 bar, there is a stable, spherically symmetric and pulsating with a standing wave frequency but motionless bubble (Fig. 2, photo b). The SBSL spectrum of water at this pressure represents the broad band continuum due to the superposition of the emission spectra of several emitters (Fig. 1, spectrum 1): OH*, H$_2$O*, possibly bremsstrahlung and thermal radiation of electrons and other “hot” particles of the non-equilibrium low-temperature plasma, periodically emerging in the bubble during acoustic vibrations at the end of the compression [3]. A similar spectral continuum of SL of the bubble (hereinafter, solvent or water continuum) is typical for many liquids. Against this background, in the SBSL spectra of the CeCl$_3$ aqueous solutions with concentrations starting from $10^{-4}$ M, we observe the exited $^*\text{Ce}^{3+}$ ion emission band with the maximum at $\sim$349 nm (hereinafter, the Ce$^{3+}$ band).

The Ce$^{3+}$ band intensity increases with the cerium concentration (Fig. 1, spectra 2–4). At the same time, the intensity of the shortwave region of the continuum (less than 300 nm) is significantly reduced due to the absorption of the emission by Ce$^{3+}$ (Fig. 1, spectra 5). The PL quantum yield of Ce$^{3+}$ in water is close to 100% [13]. This leads to the efficient re-emission of absorbed SL of the bubble, i.e. sonophotoluminescence (SPL) of the Ce$^{3+}$ emitter.

It should be noted that mass transfer through the liquid–bubble interface is limited in the case of the symmetric stationary bubble. Penetrating the non-volatile cerium ion into the bubble as a result of evaporation is inefficient and decreasing the probability of its excitation by the collision with “hot” particles of the plasma. A weak mass transfer also lowers the flow of the water sonolysis products from the bubble into the solution and the possibility of SCL of cerium ion in solution. Therefore, SPL was considered the main mechanism for the Ce$^{3+}$ SBSL generation as, besides, for the multibubble sonoluminescence (MBSL) of this emitter [14–16]. However, the stationary state of the bubble takes place only in the limited range of acoustic pressure $p_a$ affecting the bubble. Increasing and decreasing $p_a$ relative to the optimal value $\sim1.2$ bar moves the bubble around the stabilization center (Fig. 2, photos a, c). Herewith, the shape of the bubble is deformed. Indeed, there are surface waves and micro-jets, which increase the mass transfer through the interface of the bubble (in both ways, inwards and outwards) [17,18]. When $p_a=1.32$ bar, moving SBSL of water is observed. The intensity of moving SBSL continuum in the highly degassed solution has insignificant changes as compared with the SBSL intensity of the stable bubble (Fig. 1, spectrum 1). Although in our experiments, there is a general tendency for luminescence intensity to increase with increasing of $p_a$, the expected enhancement in intensity with increasing pressure to 1.3 after 1.2 bar is compensated by the appearance of moving bubble deformations, which reduce the compression efficiency and the achievable degree of collapse, on which the continuum intensity depends. When $p_a=1.16$ bar, there is no water continuum of moving SBSL (Fig. 1, background curve 6). Obviously, at this value of
Fig. 2. The photographs of the moving bubble (a, c) and the motionless bubble (b). Exposure 0.1 s. Photographs (b, c) were taken in the light of intrinsic luminescence of the bubble, photograph (a) was taken in the light reflected from an external source. Acoustic pressure, bar: 1.16 – a, 1.2 – b, 1.32 – c.

$p_a$, the energy of the bubble compression is insufficient for the appearance of a continuum due to collisional excitation of emitters. Nevertheless, even for dilute solutions of CeCl₃ in water (5·10⁻⁵ M), the Ce³⁺ emission is registered (Fig. 1, spectrum 7). At the same time, SPL of Ce³⁺ is not detected at this concentration due to the absence of SL of the bubble. Obviously, SPL is not detected at this concentration under $p_a = 1.32$ bar but the Ce³⁺ band intensity in the case of moving SBSL (Fig. 1, spectrum 8) is close to the SPL intensity of the 0.1 M Ce³⁺ solution with the stationary bubble ($p_a = 1.2$ bar). The Ce³⁺ band intensity for moving SBSL also increases with the cerium ion concentration.

As found, the Ce³⁺ band at $p_a = 1.32$ bar is quenched in acidic solutions. Thus, when H₂SO₄ added (the final acid concentration is 0.1 M) to the CeCl₃ solutions (5·10⁻⁵, 10⁻³, 0.01 M), the Ce³⁺ band intensity is reduced to the level corresponding to the SPL mechanism at $p_a = 1.2$ bar (Fig. 1, spectra 1, 2, 3 respectively). The quenching by acid (0.1 M) also takes place at 0.1 M Ce³⁺ concentration. However, there is a slight excess over the SPL intensity (the corresponding spectrum is not shown in Fig. 1). The reason for incomplete quenching at the high Ce³⁺ concentration will be considered below. Herewith, there is no significant effect of the acid addition on the solvent continuum (see also Fig. 3).

This indicates the insignificant penetration of the low-volatile acid into the bubble at this concentration (0.1 M) even under conditions of moving SBSL and weak effect on the processes of the generation of the sonolysis products. Separate experiments showed that this concentration of sulfuric acid has no significant effect on the shape and intensity of the Ce³⁺ band in the PL spectrum of CeCl₃ in water (Fig. 3, spectrum 5). Thus, the PL quantum yield of the Ce³⁺ ions in the presence of acid does not change. Therefore, quenching of moving SBSL is associated with the influence of acid on the excitation stage of cerium ion in the bulk solution. In addition, the quenching of moving SBSL of Ce³⁺ is also observed in the presence of 1 mM KBr (Fig. 3, spectrum 4). As in the case of H₂SO₄, KBr in this concentration has no significant influence on the continuums of SBSL, moving SBSL, and PL of Ce³⁺.

H₂SO₄ and KBr, more strictly the H⁺ and Br⁻ ions, used for quenching of Ce³⁺ ion moving SBSL, are known acceptors of hydrated electrons and OH radicals, respectively [19].

Based on the above facts, we consider that, except of the SPL contribution, moving SBSL of the Ce³⁺ ions represents the sonochemiluminescence. The latter consists of the sequential redox reactions occurring after the transfer of products heterolytic ($e_aq$) and homolytic (OH) water dissociation from the bubble to the CeCl₃ solution (3) and (4):

\[
\text{Ce}^{3+} + \text{OH} \rightarrow \text{Ce}^{4+} + \text{OH}^- \tag{3}
\]

\[
\text{Ce}^{4+} + e_aq \rightarrow ^{*}\text{Ce}^{3+} \tag{4}
\]

As noted in the Introduction, the formation of Ce⁴⁺ from Ce³⁺ via reaction (3) is a well-known process at the sonolysis and radiolysis of solutions of the trivalent cerium compounds [11,12]. As follows from the standard potentials $e_aq$ (~2.9 V) and Ce⁴⁺/Ce³⁺ pair (1.4 V) [12], the energy of the reduction process (no less than ~2.9 – 1.4 = ~4.3 eV) is sufficient for population of the high-energy level of the electronically excited state of Ce³⁺ (about 4.1 eV [13]) according to reaction (4). This chemiluminescent reaction is illustrated using the energy diagram of the valence sublevels of cerium ions in Supplementary material. There also is a detailed calculation of exothermicity (free energy change) of reaction (4).

The quenching of SCL is due to the reactions with acceptors (5) and (6), competing with reactions (3) and (4), respectively:

\[
\text{OH} + \text{Br}^- \rightarrow \text{OH}^+ + \text{Br} \tag{5}
\]

\[
e_{aq} + \text{H}^+ \rightarrow \text{H} \tag{6}
\]

Notably, 100 times lower concentration of Br⁻ as compared with H⁺ is enough to quench SCL. Apparently, reaction (3) is substantially slower than reaction (5). Their rate constants are $k_3 = 2.9·10^{10}$ and $k_5 = 1·10^{10}$ M⁻¹·s⁻¹, respectively [12,19]. At the same time, the reaction rates of (4) and (6) are significantly higher and close to each other: $k_4 = 6.6·10^{10}$ and $k_6 = 2.3·10^{10}$ M⁻¹·s⁻¹ [12,19].

3.2. Luminescence of Ce³⁺ during sonolysis of (NH₄)₂Ce(NO₃)₆ solutions in water

The emergence of reaction (3) was proved with special experimental studies of SBSL and moving SBSL in ceric ammonium nitrate solutions. This salt of tetravalent cerium dissolved in water manifests significant absorption in the region of Ce³⁺ band and, especially, in the short-wave region of the SBSL water continuum (its bound shifts to 340 nm, Fig. 4, spectrum 2) but the Ce⁴⁺ ion is not a luminophore.
As expected, in the absence of SPL, there is no luminescence except the unabsorbed part of the continuum in the SBSL spectra at \( p_a = 1.2 \text{ bar} \) of ceric ammonium nitrate solutions. However, in the case of the low-concentration solutions (\( 5 \times 10^{-5} \text{ M} \)), the unabsorbed part of Ce\(^{3+}\) band is observed in the spectrum of moving SBSL at \( p_a = 1.32 \text{ bar} \) (Fig. 4, spectrum 3). This fact confirms the Ce\(^{3+}\) band quenching by the Ce\(^{4+}\) reduction during the sonolysis. The Ce\(^{3+}\) band is quenched by acoustic degradation of the solution but not in the presence of KBr. These experiments confirm the fact of the Ce\(^{3+}\) generation in reaction (3).

### 3.3. Luminescence of *Ce\(^{2+}\)* during sonolysis of (NH\(_4\))\(_2\)Ce(NO\(_3\))\(_6\) solutions in ethylene glycol and estimation the possibility of chemiluminescence at Ce\(^{4+}\) reduction by reagents, other than \( e^- \)

We were able to register the well-resolved Ce\(^{3+}\) band in moving SBSL mode in the ethylene glycol solution of (NH\(_4\))\(_2\)Ce(NO\(_3\))\(_6\) (Fig. 5). In this solvent, the Ce\(^{4+}\) ion absorption in the region of the Ce\(^{3+}\) band is lower than in water, so it does not prevent for its registration. The Ce\(^{3+}\) band in ethylene glycol is quenched by H\(_2\)SO\(_4\) as in water.

The obtained data indicate that the solvated electron \( e^- \) is formed during the moving single-bubble sonolysis of ethylene glycol, which similarly to reaction (4) leads to the *Ce\(^{3+}\)* generation (reaction (4)).

\[
\text{Ce}^{4+} + e^- \rightarrow \text{Ce}^{3+} + \text{H}^+.
\]

As is known, the solvated electron may be formed during the radiolysis of alcohols, amines and amides [19]. Based on the analogy in the radiolysis and sonolysis of liquids, the heterolytic dissociation of the solvent molecules with generating \( e^- \) at the moving single-bubble sonolysis is possible in polar liquids other than water. It should be noted that it was not possible to register moving SBSL of Ce\(^{3+}\) in CeCl\(_3\) ethylene glycol solutions more than provided by SPL values. Possibly, in contrast to aqueous solutions, the ethylene glycol analog of reaction (3) providing oxidation Ce\(^{3+}\) to Ce\(^{4+}\) is ineffective. This fact does not allow observing SCL.

Hydrogen atom and carbon-centered free radicals \( \text{CH}_2\text{OH}, \text{CH}_3\text{CH}_2\text{OH} \) and \( \text{C(CH}_3)_2\text{OH} \) are also strong reducing agents formed by ultrasonic treatment of ethylene glycol solutions. The redox potentials of atom H and radicals \( \text{CH}_2\text{OH}, \text{CH}_3\text{CH}_2\text{OH} \) are \(-2.3 \text{ V} \) [12], \(-0.24 \text{ V} \) and \(-2.1 \text{ V} \) [20] respectively, and generally for hydrocarbon radicals of various nature not exceed \(-2.0 \text{ V} \) [21]. Although the reduction of tetravalent cerium (reaction (7)) by atom H (which has the highest reducing ability among the known radical intermediates of ethylene glycol sonolysis) is exothermic, the SCL generation via reaction (7) is unlikely, as in aqueous acidic solutions, where H is the main reducing agent instead of \( e^- \).

\[
\text{Ce}^{4+} + \text{H} \rightarrow \text{Ce}^{3+} + \text{H}^+.
\]

First, since the potential of the \( \text{H}^+/\text{H} \) pair \((-2.3 \text{ V})\) is 0.6 V less (in absolute value) of the standard potential of \( e^- \), the exothermicity of reaction (7) is also less than the previously found exothermicity of reaction (4) \((3.7 \text{ eV} \text{ vs} \text{ 4.3 eV})\). This energy is less than required for electronic excitation of Ce\(^{3+}\) ion, 4.1 eV. Second, even if the Ce\(^{3+}\) formation by reaction (7) is possible, its rate is \( 10^7 \text{ times lower than the rate of reaction (4)} \): \( k_f = 6.5 \times 10^7 \text{ M}^{-1} \text{ s}^{-1} \) [22]. Therefore, chemiluminescence by reaction (7) in water, as well as similar reactions of Ce\(^{4+}\) reduction by radical products in ethylene glycol, is not registered. Instead of this, in acidic solutions, where H is formed according to reaction (6), quenching of Ce\(^{3+}\) SCL is observed, as a part of moving SBSL of this ion exceeding the luminescence by the SPL mechanism.

Obviously, due to the study of the Ce\(^{4+}\) reduction processes only in acidic solutions, the radio- and sonochemiluminescence due to reaction (4) have not been previously found [11,12]. However, it should be noted that the Ce\(^{4+}\) reduction was repeatedly used in chemiluminiscent methods of the analysis of various substances, e.g. phenolic compounds [23]. In these analytical reactions, rhodamine 6G (R6G) and phenols were used as Ce\(^{4+}\) reducing reagents, and R6G was a sensitizer of luminescence. It was assumed that Ce\(^{3+}\) is the primary emitter of these chemiluminescent reactions and it is resulted from reduction Ce\(^{4+}\) to \( \text{Ce}^{3+} \). R6G, the secondary emitter with the detected luminescence, is generated by the energy transfer from the primary emitter. Meanwhile, the excitation of trivalent cerium ion in the described reaction is questionable. The reduction potential of R6G \((-0.8 \text{ V})\) coupled with the oxidizing potential of Ce\(^{4+}\) is insufficient to create the energy reserve necessary for populating the excited state of Ce\(^{3+}\). However, there is no direct spectral identification of Ce\(^{3+}\) in this and other similar studies [25] postulating reaction Ce\(^{4+}\) to \( \text{Ce}^{3+} \).

We found only one previous work [26] with the CL emission spectrum confirming the formation of Ce\(^{3+}\) during the reduction of tetravalent cerium. The Ce\(^{3+}\) ion is formed in heterogeneous system \((\text{NH}_4)_2\text{Ce(NO}_3)_6 \rightarrow \text{Ce}^{3+} + \text{H}_2\text{O} \) as a result of the interaction of the catalytically active surface of the \((\text{NH}_4)_2\text{Ce(NO}_3)_6 \) crystals with water. The redox potentials of pairs Ce\(^{3+}/\text{Ce}^{4+}\) (+1.4 V) and H\(_2\)O/H\(_2\) are \(-1.23 \text{ V}\). The maximum of the Ce\(^{3+}\) band in ethylene glycol is shifted by 15 nm to the long-wave region relative to that one in water.

Fig. 4. The spectra of SBSL at 1.2 bar (1, 2) and moving SBSL at 1.32 bar (3): 1 – H\(_2\)O; 2, 3 – \( 5 \times 10^{-5} \text{ M} \) (NH\(_4\))\(_2\)Ce(NO\(_3\))\(_6\). 4 – Absorption spectrum (cuvette \( l = 0.5 \text{ cm} \)) of \( 10^{-5} \text{ M} \) (NH\(_4\))\(_2\)Ce(NO\(_3\))\(_6\) in H\(_2\)O. The dashed line shows the “restored” Ce\(^{3+}\) band in spectrum 3 in the absence of light absorption by the Ce\(^{4+}\) ion.

Fig. 5. The spectra in ethylene glycol: 1 – SBSL (1.24 bar) without additives; 2 – moving SBSL (1.36 bar) of \( 5 \times 10^{-5} \text{ M} \) (NH\(_4\))\(_2\)Ce(NO\(_3\))\(_6\), 3 – moving SBSL (1.36 bar) \( 5 \times 10^{-5} \text{ M} \) (NH\(_4\))\(_2\)Ce(NO\(_3\))\(_6\), 0.1 M H\(_2\)SO\(_4\), 4 – PL (\( \lambda_{\text{exc}} = 253 \text{ nm} \)) of \( 10^{-5} \text{ M} \) CeCl\(_3\), 5 – Absorption (cuvette \( l = 1 \text{ cm} \)) of \( 5 \times 10^{-5} \text{ M} \) (NH\(_4\))\(_2\)Ce(NO\(_3\))\(_6\).
Thus, moving SBSL of Ce$^{3+}$ in the aqueous solutions of inorganic salt CeCl$_3$ has three mechanisms in contrast to SBSL having only the SPL mechanism. These are SCL at Ce$^{3+}$ concentrations less than $10^{-4}$ M, SCL + SPL in the concentration range of $10^{-4}$–$10^{-2}$ M, and SCL + SPL + CE at [Ce$^{3+}$] $> 10^{-2}$ M. The multibubble sonoluminescence of cerium ions, despite its apparent similarity to moving SBSL, represents only SPL at [Ce$^{3+}$] $= 10^{-4}$–$10^{-2}$ M and, apparently, SPL + CE at large concentrations due to absence of $e_{aq}$ among the primary products of water decomposition in this mode of sonolysis [7,31,32] and accordingly SCL.

4. Conclusion

In this work, we have studied the moving single-bubble sonoluminescence of the Ce$^{3+}$ ion in the solutions of CeCl$_3$ and (NH$_4$)$_2$Ce(NO$_3$)$_6$ in water and ethylene glycol. It has been shown that the significant amount of intensity of this luminescence (100% under concentrations less than $10^{-4}$ M) is due to the sonochemiluminescence in the reactions of the products of water sonolysis (decomposition) in the bubble. The reduction of the tetravalent cerium ion by the solvated (or hydrated) electron Ce$^{4+} + e_{aq} \rightarrow $ Ce$^{3+}$ is a key stage of this sonochemiluminescence.

CRediT authorship contribution statement

Glyus L. Sharipov: Conceptualization, Project administration, Writing - original draft, Writing - review & editing, Investigation, Validation, Funding acquisition. Bulat M. Gareev: Investigation, Writing - original draft, Validation. Kristina S. Vasilyuk: Investigation, Writing - original draft. Dim I. Galimov: Investigation, Project administration, Writing - original draft, Writing - review & editing. Airat M. Abdakhmanov: Investigation, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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