Synergy between low and high energy radical femtochemistry

YA Gauduel
Laboratoire d’Optique Appliquée, CNRS UMR7639, Ecole Polytechnique ParisTech - ENS Techniques Avancées ParisTech, 91761 Palaiseau Cedex, France and Radiation Biology MELUSYN Network, Armir-Collège de Polytechnique, Paris, France.

E-mail: yann.gauduel@ensta-paristech.fr

Abstract. The deleterious effects of ionizing radiation on integrated biological targets being dependent on the spatio-temporal distribution of short-lived radical processes, a thorough knowledge of these early events requires a real-time probing in the range $10^{-15}$ – $10^{-10}$ s. This manuscript review is focused on the synergy that exists between low (1-10 eV) and high (MeV) energy radiation femtochemistry (LERF, HERF respectively). The synergy remains crucial for the investigation of primary radical processes that take place within the prethermal regime of low energy secondary electrons. The quantum character of very-short lived electron in a prehydrated configuration provides a unique sub-nanometric probe to spatially explore some early radiation-induced biomolecular damage. This approach would foreshadow the development of innovative applications for spatio-temporal radiation biology such as, i) a highly-selective pro-drug activation using well-defined quantum states of short-lived radicals, ii) the real-time nanodosimetry in biologically relevant environments, and iii) the ultrashort irradiation of living cells.

1. Introduction
It is commonly admitted that the spatial distribution of radicals can be decisive for the induction and amplification of early biomolecular damage induced by different types of radiations (X and UV photons, relativistic particles, accelerated ions) [1-6]. From a fundamental point of view, one challenge concerns the complete understanding of multiscale events triggered by an initial energy deposition inside confined clusters of ionization and evolving over several orders of magnitude, typically from femtosecond ($1fs = 10^{-15}$s) and sub-micrometric scales. In condensed phase, the investigation of elementary radical reactions can be carried out in strong synergy with the most recent progresses of ultra-short laser sources and low or high energy radiation femtochemistry [6-8].

One of the most fundamental aspects of biomolecular damage triggered by radiations concerns the dissociative electron attachment processes that take place in confined ionization spaces. Such processes involve a hierarchy of secondary electron populations for which the energy varies from the thermal value ($kT \sim 0.025$ eV) to the sub-excitation and relativistic levels i.e. few eV, MeV respectively (figure 1). In presence of water molecules, the solvent of life, the primary radical processes induced by an electron attachment can be assisted or impeded by ultrafast caging process such as solvation phenomena, solvent bridged pair formation. The microscopic understanding of primary radical processes that are triggered by ionizing radiation requires the real-time probing of
multiple non-equilibrium states whose the lifetimes are typically in the sub-picosecond regime. In this way, prethermal processes and sub-structure of tracks can play a crucial role at early time.

![Diagram](image_url)

**Figure 1.** Relationship between low and high energy electrons involved in ultrafast electron attachment and dissociative process on biomolecules (BM). In aqueous environment, time dependent caging effects assist dissociative processes (bond making-bond breaking) and early radical events.

2. **Low energy femtoraical chemistry in condensed phase**

With the intensive development of ultra-short laser technologies and advanced high-time resolved spectroscopic methods, the course of short lived non-equilibrium radical trajectories are more and more observable on the molecular motion scale [7].

2.1 **LERF of water molecules**

In the framework of non-linear interactions of pure water molecules with ultra-short high energy UV pulses whose the peak power density is around \(10^{10} \text{ W.cm}^{-2}\), a direct excitation can be triggered by a two-photon process. For wave plane propagation through an aqueous sample, this phenomenon is expressed by the equation 1:

\[
\frac{\partial Y}{\partial t} + \left( \frac{1}{v} \right) \frac{\partial Y}{\partial x} = -B I^2
\]

for which I is the radiation intensity, B the two photon absorption coefficient and v the light velocity in the medium.

Considering an excited \(A^+\) state (1b1 \(\rightarrow\) 3a1 for instance), a nonlinear two-photon UV excitation process (\(E_{\text{Excit}} = 2 \times 4 \text{ eV}\)) can be used to investigate the LERF signals dynamics of early water molecules radical processes. Femtosecond UV-IR absorption spectroscopic investigations in the energy range 3 - 1 eV allow to discriminate the sequential events of multiple radical channels (figure 2). The non-linear two-photon energy deposition of 8 eV in a water bulk triggers early water defects such as the hydronium ion and hydroxyl radical via an ultrafast positive hole \(H_2O^+\) reaction, multiple
non-equilibrium delocalized electron configurations (quasi-free delocalized electron \(\{e^{-}_{qf}\}\), p-like excited prehydrated electron \(\{e^{-}_{p}\}\), electron-radical pairs and hydrated electron ground state \(\{e^{-}_{s}\}\)). All these transient radical pathways take place in less than \(5 \times 10^{-13}\) s.

![Diagram](image)

**Figure 2.** LERF of water molecules. Upper part: Electronic absorption spectrum of the first and second excited states of water molecules in the UV region. Middle and lower parts: Energy level diagrams of femtosecond two-photon excitation of water molecules leading to multiple radical pathways (early products). Some LERF signals probed at different wavelengths, in the UV-IR spectral range, are reported on the right part. Adapted from [7 and 10].
A direct electron photodetachment in the vicinity of water conduction band takes place in less than 250 fs. This primary phenomenon leads to an electron hydration via the relaxation of infrared 2p-like excited prehydrated electron: $2p(e_{\text{prehyd}}) \rightarrow 1s(e_{\text{hyd}})$ transition [12-13]. LERF experiments have also shown that an ultrafast pathway contributes to transient solvent bridged three-bodies complex $[\text{OH}^*\cdots e^\cdots \text{H}_3\text{O}^+]$ (figure 3).

![Diagram](image)

**Figure 3.** LERF of short-lived three-bodies complex $[\text{OH}^*\cdots e^\cdots \text{H}_3\text{O}^+]$ following a femtosecond two-photon UV excitation of water molecules in liquid phase. Adapted from [7,10].

The LERF of transient radical complexes supports the conclusion that $[\text{H}_3\text{O}^*\cdots e^\cdots \text{OH}]_{\text{al}20}$ deactivation ($0.29 \times 10^{13}\text{ s}^{-1}$) is comparable to the estimate of a vibrationally excited water molecules relaxation ($\nu_{\text{H}_2\text{O}^*} \sim 0.33 \times 10^{13}\text{ s}^{-1}$) [14]. Indeed, LERF of neat liquid water contribute to deeply understand i) the nature of early branching between ultrafast radical pathways, ii) the contribution of ultrashort-lived solvent configurations to multiple potential energy surface crossing zones [15].

### 2.2 Ultrafast protic radical events in well-defined configurations

A fundamental question about early radical reactions in solution concerns the role of microscopic solvent dynamics during the reorganization of charge distribution. The understanding of solvent effects involved in the definition of reaction dynamic factors encompasses the synergy between high-time resolution of short-lived transition states and advances in computational solution chemistry [16-24]. Aqueous ionic solutions represent complicated many body systems and a paradigm for the investigation of elementary radical processes for which solvent caging effects can assist or impede reactive modes. An archetype concerns a dehydrogenation process for which a concerted electron-proton transfer can be considered as a transient state of the reaction pathway (equation 2).

\[
\begin{align*}
\left\{ \begin{array}{c}
R^+ \\
A^-
\end{array} \right\}_{S} & \xrightarrow{\text{Excitation}} \left\{ \begin{array}{c}
\text{RH}^* \\
A^-
\end{array} \right\}_{S} \\
& \xrightarrow{\text{Ionization}} \left\{ \begin{array}{c}
\text{RH} \cdots e^* \\
A^-
\end{array} \right\}_{S} \\
& \xrightarrow{T.E.} \left\{ \begin{array}{c}
\text{H}^+ \cdots e^- \\
A
\end{array} \right\}_{S} \\
& \xrightarrow{\text{Resolvation}} \left\{ \begin{array}{c}
R^- \\
A
\end{array} \right\}_{S}
\end{align*}
\]

(2)
The protic nature of water molecules may influence the quantum aspects of unbound/bound electron states, mainly during short-time concerted electron-proton transfer [25-30]. Indeed, femtosecond IR spectroscopy of elementary electron transfers in acid solutions offers the opportunity to investigate different early partitions between reactive and nonreactive pathways (figure 4). In concentrated hydrochloric acid solution (molecular ratio H₂O/HCl = 5), water molecules are shared by chloride ions and hydronium ions; consequently the Grothuss mechanism is totally abolished [31]. With such conditions an ultrafast 2p-state electron transfer reaction with an aqueous proton (hydronium ion) is not observed. However, when the delocalised electron is trapped ~ 1 eV below the p-like electron level, an efficient prehydration electron-proton reaction takes place via a short-lived three-body complex (Y...e⁻...H⁺) with Y=Cl. Femtosecond investigations have established that a well defined hydrogen bond ring structure {Cl...e⁻...H⁺}aq connecting a halide ion with an hydrated proton favors an efficient electron-proton reaction with a frequency rate of 4 x 10^{12} s⁻¹ (figure 4).

This ultrafast electron-proton reaction is mainly governed by a transition state for which a delocalized electron oscillates between a polarizable Cl atom and the dihydronium ion, before an electron collapse with the hydrated proton. Considering semi-quantum MD simulations, the 4s character of a delocalised electron in the vicinity of Cl atom would be more favourable for an ultrafast electron transfer that the 2p-state excited electron [32]. The potential energy surface crossing zone would correspond to an “inverted Marcus region” [33]. The discrimination of vibrational modes during the formation of the pre-reactive three-body complex (Y...e⁻...H⁺) argues for the contribution of selective solvent modes such as a vibration of torsional type or stretching mode of hydrogen bridge OH...O. The discrimination of high frequency modes around 65 cm⁻¹ is assigned to the flexion of O-H...O within a hydrogen bond network. Consequently, a solvent caging effect involving vibronic couplings would assist an electronic migration on the potential energy surface of the hydrated proton.

Figure 4. Ultrafast electron transfer trajectory inside the spherical volume of well-coordinated [Cl...n H₂O...H⁺] complex. Water caging effects characterized by specific vibrational modes assist the electron trajectory form excited CTTS states of chloride ion (excited Charge Transfer to Solvent State). The effective radius of this electron transfert is dependent on isotopic substitution and R value of the aqueous ionic solution [11].
The LERF investigations of early radical processes occurring in aqueous environments provide guidance for understanding the role of solvent-bridged electron-radical complexes in aqueous clusters of ionization triggered by high energy radiations.

3. High energy radiation femtochemistry of nascent tracks

The wide impact of ionizing radiation for biomedical applications (radiation biology and cancer radiotherapy) concerns the interactions of high-energy particles or photons (electron, proton, X and γ rays) with complex biomolecular architectures. Such interactions induce electronic or vibrational excitations, ionizations, ultrafast radical phenomena and primary molecular damage such as DNA strand breaks. These early radiation events take place in confined spaces, commonly called tracks or spurs. Numerous pulsed radiolysis experiments performed from microsecond to picosecond scales have greatly enhanced our understanding of water radiation chemistry and radical processes in tracks, considering nonhomogeneous and homogeneous regimes [4,5,34-41]. In nascent spurs, the escape probability of secondary low energy electrons would be influenced by ultra-fast recombination with two neoformed OH, H₃O⁺ entities. These primary radical events would influence the yield of water decomposition products at early times. Up to now the indirect determination of the primary yield of fully relaxed hydrated electrons, a ubiquitous reducing radical stabilized by water molecules and whose the interaction potential with water bath is around -2.8 V [42-44], has been the subject of numerous investigations using linear accelerators. The quantum character of this molecular hydrogen precursor (1s-like ground state) [45-49] greatly determines the behavior of multiple radical and redox reactions in irradiated aqueous environments. Consequently, the early fate of hydrated electrons in nascent spurs is of particular relevance but has never been observed at early time after an energy deposition.

In this context, some recent innovative high-energy laser techniques open new opportunities for the development of femtosecond investigations of low-energy electron fate in radiation-induced aqueous nascent tracks. With the advent of powerful laser systems (TW laser), laser plasma interactions [8,9,50-54] can now provide high-energy, femtosecond electron bunches and allow the real-time probing of ultrafast radical events in nascent tracks (figure 5).

![Figure 5](image-url) **Figure 5.** Left: Experimental set-up used for the development of HERF in aqueous liquid phase [9,55]. The energy of the femtosecond relativistic electron bunches is in the range 3-15 MeV. The Femtolysis detection uses a perpendicular pump (electron bunch) – probe (optical pulse) configuration. Right: Calculated estimate of the yield of hydrated electrons at early time \(G(e⁻_{aq})_{ET}\) from femtolysis water experiments performed in the temporal range 0-150 ps. The estimated \(G(e⁻_{aq})_{ET}\) value at \(t_{max} \approx 5\) ps equals 6.5 ± 0.5 molecules / 100 eV.
FEMTOLYSIS (FEMTOsecond radioLYSIS) of pure liquid water has been performed by using an innovative laser produced high-energy, ultra-short electron bunches in the 2.5-15 MeV range and High Energy Radiation Femtochemistry (HERF) measurements [55]. The short-time monitoring of a primary reducing radical, hydrated electron $e_{aq}$, has been performed in confined ionization spaces (nascent spurs). The calculated yield of hydrated electrons at early time, $G(e_{aq})_{ET}$, is estimated to be $6.5 \pm 0.5 \text{(number/100 eV)}$ at $t \sim 5 \text{ ps}$ after the ultrafast energy deposition [55]. This estimated value is high compared to i) the available data of previous works that used scavenging techniques, ii) the predictions of stochastic water radiolysis modelling for which the initial behaviour of hydrated electron is investigated in the framework of a classical diffusion regime of independent pairs. The HERF data give new insights into the early ubiquitous radical escape probability in nascent aqueous spurs and emphasize the importance of short-lived solvent bridged electron-radical complexes $[H_3O^+...e_{aq}...OH]_{11230}$ (non-independent pairs). A complete understanding of the $G(e_{aq})_{ET}$ value needs to account for quantum aspects of 1s-like trapped electron ground state and neoformed prototropic radicals that govern ultra-fast recombination processes via non-independent pair configurations. Indeed, the predicted estimate of $G(e_{aq})_{ET}$ value at $t \leq 5 \text{ ps}$ would be compared with the predictions of future quantum mechanical theories on ultrafast electron-radical pair dynamics in nascent spurs.

These FEMTOLYSIS data would request the semi-quantum modeling of early spatial secondary electron trajectories, considering the kinetic energy scattering and localization process. Further HERF researches will more deeply investigate several fundamental aspects such as the complex branching between ultra-fast excitation and ionization pathways in tracks - the relationship between sub-picosecond electron prehydration and ultrafast formation dynamics of $H_2O^+$, OH or $H_3O^+$ within non-independent radical pairs - the initial 3D spatio-temporal distribution of primary radical products inside heterogenous structures of native tracks. Regarding i) the recent developments of low energy bioradical femtochemistry of water molecules for which the “2p-like prehydrated electron” may exert a major role in biomolecular damage [57-60], ii) the advances in modules of the physical-biophysical Monte Carlo track structure codes [39] and iii) the quantum chemistry of radiations interactions with biomolecules [39], we should wonder whether ultrafast radiation damage occurring in the prethermal regime of secondary electrons represent a tenuous frontier between direct and indirect effects.

4. LERF and HERF of prethermal radical processes

Ultrafast radical events occurring in less than 1ps ($10^{-12}$s) after ionizing radiation deposition represent a specific domain for which the quantum character of short-lived events is preeminent. This is particularly important when biomolecular damage take place in the prethermal regime of secondary electrons (figure 1). Following a local energy loss around 20 eV deposited by a relativistic particle on a distance shorter than 100 Å, the secondary electrons scatter progressively their excess energy within a sub-micrometric environment. In the specific prethermal regime, the partially localized electron energy is still higher than the thermal energy $kT$ i.e. $E \sim 0.025 \text{ eV}$. As the primary biological target damages induced by ionizing radiations are highly dependent on the survival probability of low energy secondary electrons, a thorough knowledge of their short-range interactions with neighboring molecules requires the real-time probing of early events inside nanometric clusters of ionization.

In the framework of an energy/space/energy profile, the prethermal regime of localized electrons corresponds to the specific temporal window 0.1-10 ps. A major stride of biological interest concern the ultrafast radical processes mediated by p-like excited prehydrated electron. The LERF of biomimetic organized assemblies containing oxidized pyridine nucleotides (NAD^+, NMN^+) [61] or disulfide biomolecules [57] has demonstrated that very short-lived localized electrons contribute to ultrafast radical processes (figure 6).

During the prethermal regime, the activate barrier of a reduction process involves a crossing zone between a subpicosecond radiationless $p \rightarrow s$ transition and an efficient “p state” excited electron attachment on the biomolecule. It has been clearly established that a nondiffusive electron transfer involving an IR p-like electron is about $4.4 \times 10^7$ time faster than a diffusion-controlled reaction with a hydrated electron ground state (1s state) [57,62,63]. Considering the similarity of pyridine nucleotides
with DNA components, the pioneering LERF works on ultrafast pyridinyl radical processes induce an open question: Do prehydrated electron trigger direct DNA damage and mutagenic effect? Recent works performed under UV/ionizing radiation have established that femtosecond one-electron reductions of 5-halo-2'-deoxyuridines (potential radiosensitizing agents increasing the biological effects of radiations) and other nucleotides could be induced by prehydrated electron [58,63,64].

**Ultrafast low energy electron attachment**

2p like excited configuration

![Diagram of energy level diagram of an ultrafast one-electron attachment on oxidized pyridine nucleotide (NAD⁺) in aqueous environment. This process involves a 2p-like excited electron state and leads to the formation of a pyridinyl radical.](image)

**Figure 6.** Energy level diagram of an ultrafast one-electron attachment on oxidized pyridine nucleotide (NAD⁺) in aqueous environment. This process involves a 2p-like excited electron state and leads to the formation of a pyridinyl radical.

During the last decade, the LERF of prethermal radical processes has also been conducted with disulfide biomolecules whose cystamine, the reactive center of oxidized glutathione [57]. The interest of this biological disulfide is two-fold: the limited number of atoms for real-time investigations and clinical properties in living systems [66]. The direct attachment of a delocalized electron on a disulfide biomolecule has been observed in real time by femtosecond IR spectroscopy of homogeneous solutions or organized assemblies. The early partition between reactive ($\{e^{-}_{IR}\}_{Reac}$) and nonreactive ($\{e^{-}_{IR}\}_{p->s}$) electronic configurations could be determined from the following expression:

\[
\frac{\alpha^{oT}}{\alpha^{oT}_{p->s}} \frac{\{e^{-}_{IR}\}_{Reac}}{\{e^{-}_{IR}\}_{p->s}} = \frac{\sigma^{oT}_{Reac}}{\sigma^{oT}_{p->s}} \cdot \frac{P_{Reac}}{P_{p->s}}
\]

(3)

In this expression, $P_{Reac}$, $P_{p->s}$ represent respectively the probability of a prehydration univalent reduction form a 2p-like excited electron and an electron salvation process via a 2p→1s transition. The probability of a prehydration univalent reduction $P_{Reac}$ is defined as follows:

\[
\frac{P_{Reac}}{P_{p->s}} = \frac{\alpha^{oT}}{\alpha^{oT}_{p->s}} \frac{\{e^{-}_{IR}\}_{Reac}}{\{e^{-}_{IR}\}_{p->s}}
\]

(4)
In equations 3-5, the adjusted parameter $\alpha_{\omega i}^{oT}$ represents the spectral contribution of an electronic state $\omega = 1$ at 0.99 eV. The subpicosecond competition involving the ultrafast electron attachment on cystamine and the energy gap relaxation from the first excited state to the ground state of trapped electron is characterized by a high branching ratio ($P_{\text{Reac}} / P_{p \rightarrow s} \approx 0.91$). This ultrafast radical process would involve some distortions of p-like orbitals of prehydrated electron in the vicinity of a sulfur-sulfur bond. The sub-picosecond lifetime of IR $e^{-p}$ represents a temporal limit for that an early SS bond energy rearrangement facilitates an electron tunnelling through a potential barrier separating the IR p-state electron of an unpaired electron. In this way, the calculated effective radius $r_{\text{eff}}$ of a cystamine molecule involved in the non-equilibrium p-like excited electron attachment equals 9.8 Å. Regarding the native RS-..SR- radical anion, the antibonding electron contributes to the formation of a 2center-3 electron bond in less than 600 fs [57,67].

In synergy with these LERF investigations, the early radiation-induced biomolecular target damage in nascent ionization tracks are been recently investigated by HERF, using ultra-short relativistic electron beams in the energy range 3-15 MeV and ultrafast spectroscopic methods. Following a dose of 15 Gy delivered in less than 500 fs, an ultrafast collapse takes place between low energy electron (precursors of fully hydrated electrons) and cystamine molecules localized in the chemical core i.e. at the interface between the physical core and penumbra zone. The early quantum yield of fully hydrated electrons in native tracks argues for a prethermal one-electron attachment on a disulfide biomolecule (cystamine) in less than $8.5 \times 10^{-12}$ s. Consequently, the anionic radical formation of cystamine (RS-..SR$^{\text{aq}}$) with R = NH$_2$ (CH$_2$)$_2$ occurs faster than the radiationless $2p \rightarrow 1s$ transition of prehydrated electrons. In the future, predictive ionizing radiation effects on more complex biomolecular systems would be obtained in the framework of spatio-temporal correlations of energy deposition. In this way, disulfide molecules can be considered as a sensor of ultrafast oxidation-reduction phenomena involving sulfur-centered radical anion (RS-..SR$^-$). Time-resolved spectroscopic studies of a $2\sigma/1\sigma^*$ sulfur-sulfur bond dynamics from thiol monomers or disulfide biomolecule open a new era for sulfur biochemistry and provide guidance for further theoretical investigations of short-time solvent cage effect during a $2\sigma/1\sigma^*$ sulfur-sulfur bond breaking.

5. Future challenges and concluding remarks

The emerging HERF domain provides guidance for resolving some fundamental aspects of high energy radiation induced radical events during the nonhomogeneous regime of nascent tracks (figure 7). In this way, the synergy between LERF and HERF suggests that the quantum character of trapped electron and ultrashort-lived water cation would greatly influence the dynamics of ultrafast water bridged electron-radical complexes (non independent pairs). From a theoretical and computational point of view, the stochastic modelling of ultrafast radical processes would be upgraded, taking into account the quantum character of nonequilibrium electronic configurations during the prethermal regime of very low energy electrons in radiation tracks.

The real-time investigation of interactions between relativistic particle and biomolecular targets opens exciting opportunities for the sensitisation of confined environments (groove of DNA, protein pockets) to ionising radiation on the time scale of molecular motions, i.e. angstrom or sub-angstrom displacements. Potential advances are expected in the next decade, mixing the characteristics of ultrashort micro beams of relativistic particles with those of femtosecond X ray sources. High-time resolved X-ray or electron diffractions of transient states are in progress. The spatio-temporal resolution of transient structures represents some innovating applications of lasers to investigate reaction pathway at the atomic and molecular levels.
### Fundamental Aspects of High Energy Radical Femtochemistry

| Theoretical Radiation Chemistry | Time / S   | New developments                       |
|--------------------------------|-----------|----------------------------------------|
| Energy deposition              | $10^{-13}$| Real Time Probing of Initial Events     |
| Stopping power                 | $10^{-17}$|                                        |
| Response of matter to energy absorption | $10^{-15}$| Prethermal Radical Chemistry            |
| Dry hole migration ($H_2O^+$)  | $10^{-14}$|                                        |
| Physical track structure       | $10^{-13}$| Early Molecular Damage                  |
| Mechanism of thermalization and hydration | $5 \times 10^{-13}$|                                        |
| Semi-quantum MD simulations    | $10^{-12}$|                                        |
| Shape and sizes of track entities | $10^{-11}$|                                        |
| Chemical track structure       | $10^{-12}$|                                        |
| Relationships of partial differential equations to track models in prescribed diffusion and Monte Carlo techniques | $10^{-9}$ | $10^{-8}$ |
[8] Faure J, Rechatin C, Norlin A, Lifschitz A, Glinec Y and Malka V 2006 Nature 444 737.
[9] Malka V, Faure J, Gauduel Y, Lefebvre E, Rousse A and Ta Phuoc K 2008 Nature Phys. 4 447.
[10] Gauduel Y 1994 Ultrafast electron-proton reactivity in molecular liquids In Simon JD Ultrafast Dynamics of Chemical Systems 81 (Kluwer Publisher).
[11] Gauduel Y and Gelabert H 2000 Chem. Phys. 256 333.
[12] Migus A, Gauduel Y, Martin JL and Antonetti A 1987 Phys. Rev. Lett. 58 1159.
[13] Gauduel Y, Pommeret S and Antonetti A 1993 J. Phys. Chem. 97 134.
[14] Henly E and Johnson E 1987 The Chemistry and Physics of high energy reactions (University Press).
[15] Laenen R and Roth T 2001 J. Mol. Structure 598 37.
[16] Cramer CJ, Truhlar DG 1994 Structure and reactivity in aqueous solution, (ACS Symposium, Washington).
[17] Levine RD, Berstein DG 1987 Molecular Reaction Dynamics and Chemical Reactivity (Oxford: University Press).
[18] Moreau M and Turq P 1988 Chemical reactivity in liquid: fundamental aspects (Plenum Press)
[19] Gauduel Y and Rossky PJ 1994 Ultrafast Reaction Dynamics and Solvent Effects (New York: AIP Press).
[20] Gauduel Y and Borgis D 1996 Elementary chemical processes in liquids and solutions Special issue of J. Chim. Phys. 93 1577.
[21] Zewail HA 2000 J. Phys. Chem. A, 104 5660.
[22] Bagchi B 1989 Ann. Rev. Phys. Chem. 40 115.
[23] Allen MP and Tildesley DJ 1987 Computer simulation of liquids (Oxford SciencePublications)
[24] Castelman W 2006 Femtochemistry VII Fundamental ultrafast processes in chemistry, physics and biology (Elsevier).
[25] Franck F 1985-1989 Water Science Reviews (Cambridge University Press).
[26] Laasonen K, Sprik M, Parrinello M and Car R 1993 J. Chem. Phys. 99 9080.
[27] Tuckerman M, Laasonen K, Sprik, M and Parrinello M 1995 J. Chem. Phys. 103 150.
[28] Vuilleumier R and Borgis D 1999 J. Chem. Phys. 111 4251.
[29] Elsaeesser T and Bakker HJ 2002 Ultrafast Hydrogen Bonding Dynamics and Proton Transfer Processes in the Condensed Phase (Kluwer Publishers).
[30] Bakker HJ, Kropman MF, Omta AW 2004 Ultrafast motion of water molecules near ions In Martin MM and Hynes JT Femtochemistry and Femtobiology 149 (Elsevier, Amsterdam).
[31] Agmon N 1998 J. Phys. Chem. 102 192.
[32] Staib A and Borgis D 1996 J. Chem. Phys. 104 9027.
[33] Marcus RA 1993 Rev. Mod. Phys. 65 599 and references therein.
[34] Baxendale JH and Busi F 1982 The Study of Fast Processes and Transient Species by Electron Pulse Radiolysis (Dordrecht: Reidel Publishing Company).
[35] Farhataziz and Rodgers M 1987 Radiation Chemistry (Weinheim VCH).
[36] Freeman GR 1987 Kinetics of nonhomogeneous processes (New York: Wiley).
[37] Goodhead DT 1989 Int. J. Radiat. Biol. 56 623.
[38] Jonah CD and Madhava Rao BSM 2001 Radiation Chemistry: Present Status and Future Trends (Amsterdam: Elsevier).
[39] Sabin JR and Brandas E 2007 Advances in quantum chemistry: theory of the interaction of radiation with biomolecules (Amsterdam: Elsevier).
[40] Friedland W, Paretzke HG, Ballarini F, Ottolenghi A, Kreth G and Cremer C 2008 Radiat. Environ. Biophys 47 49.
[41] Shukla M and Leszczynski J 2008 Radiation induced molecular phenomena in nucleic acids (Springer).
[42] Hart EJ and Anbar M 1970 The Hydrated Electron (New York: Wiley).
[43] Jonah CD, Hart EJ and Matheson MS 1973 J. Phys. Chem. 77 1838.
[44] Gopinathan C and Girija G 1983 Radiat. Phys. Chem. 21 209.
[45] Schnitker J and Rossky PJ 1987 *J. Chem. Phys.* **86** 3471
[46] Wallqvist A, Martyna G and Berne BJ 1988 *J. Phys. Chem* **92** 1721.
[47] Neria N, Nitzan A, Barnett RN and Landman U 1991 *Phys. Rev. Lett.* **67** 1011.
[48] Tuckerman M, Laasonen K, Sprik M and Parrinello M 1995 *J. Phys. Chem.* **99** 5749.
[49] Yang CY, Wong KF, Skaf MS and Rossky PJ 2001 *J. Chem. Phys.* **114** 3598.
[50] Faure J, Glinec Y, Pukhov A, Kiselev S, Gordienko S, Lefebvre E, Rousseau JP, Burgy F and Malka V 2004 *Nature* **431** 541.
[51] Crowell RA, Shkrob IA, Oulianov DA, Korovyyanko O, Gosztola DJ, Li Y and Rey de Castro RC 2005 *Nucl. Inst. Met. Phys. Res.* **241** 9.
[52] Oulianov DA, Crowell RA, Gosztola DJ, Shkrob IA, Korovyyanko OJ and Rey-de-Castro RC 2007 *J. Appl. Phys.* **101**, 053102-1-9.
[53] Rechatin C, Faure J, Ben-Ismail A, Lim J, Fitour R, Specka A, Videau H, Tafzi A, Burgy F, and Malka V 2009 *Phys. Rev. Lett.* **102** 164801
[54] Esarey E, Schroeder CB and Leemans WP 2009 *Rev. Mod. Phys.* **81** 1229
[55] Brozek-Pluska B, Glíger D, Hallou A, Malka V and Gauduel Y 2005 *Rad. Phys. Chem.* **72** 149.
[56] Gauduel YA, Glinec Y, Rousseau JP, Burgy F and Malka V 2010 *Eur. Phys. J. D* **60** 121.
[57] Gauduel Y, Gelabert H and Guilloud F 2000 *J. Am. Chem. Soc.* **122** 5082.
[58] Gauduel Y, Glinec Y and Malka V 2007 *SPIE Proceedings* **6449** E1.
[59] Wang JCR, Nguyen J and Lu QB 2009 *J. Am. Chem. Soc.* **131** 11320.
[60] Sanche L 2009 *Nature* **461** 358.
[61] Gauduel Y, Berrod S, Migus A, Yamada N and Antonetti A 1988 *Biochemistry* **27** 2509.
[62] Gauduel Y, Sander M and Gelabert H 1998 *J. Phys. Chem. A* **102** 7795.
[63] Gauduel Y, Hallou A and Charles B 2003 *J. Phys. Chem. A* **107** 2011.
[64] Wang CR and Lu QB 2007 *Angew. Chem. Int. Ed.* **46** 6316.
[65] Lu QB 2010 *Mutation. Res. Rev.* **704** 190.
[66] Bergamini, A, Capozzi, M, Ghibelli, L, Dini, L, Salanietro, A, Milanese G, Wagner T, Beninati S, Delfina CD, Amici C and Rocchi G 1994 *J. Clin. Invest.* **93** 2251.
[67] Gauduel Y, Glinec Y and Malka V 2008 *J. Phys. CS* **101** 012004.
[68] Malka V, Faure J and Gauduel Y 2010 *Mutation. Res. Rev.* **704** 142.
[69] Lacombe S, Sabatier L, Wien F and Gauduel YA 2010 *Cell Death Disease* **1** e4.
[70] Rigaud O, Fortunel NO, Vaigot P, Cadio E, Martin MT, Lundh O, Faure J, Rechatin C, Malka V and Gauduel YA 2010 *Cell Death Disease* **1** e73.