



HAL
open science

Formulation induces direct DNA UVA photooxidation. Part I. Role of the formulating cationic surfactant

Johanne Teychené, Dalina Didacus-Prins, Nadia Chouini-Lalanne, Valérie Sartor, Christophe Dejugnat

► To cite this version:

Johanne Teychené, Dalina Didacus-Prins, Nadia Chouini-Lalanne, Valérie Sartor, Christophe Dejugnat. Formulation induces direct DNA UVA photooxidation. Part I. Role of the formulating cationic surfactant. *Journal of Molecular Liquids*, 2019, 295, pp.111712. 10.1016/j.molliq.2019.111712. hal-02322463

HAL Id: hal-02322463

<https://hal.science/hal-02322463>

Submitted on 20 Jul 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

1 Formulation induces direct DNA

2 UVA photooxidation. Part I. Role of 3 the formulating cationic surfactant

4 *Johanne Teychené, Dalina Didacus-Prins, Nadia Chouini-Lalanne, Valérie Sartor*,*
5 *Christophe Déjugnat**

6
7 Laboratoire des IMRCP, Université de Toulouse, CNRS UMR 5623, Université
8 Toulouse III - Paul Sabatier

11 **Abstract**

12 Cethyltriethylammonium bromide (CTEAB) was considered as a cationic surfactant to
13 form lipoplexes with DNA. In TRIS/HCl buffer, CTEAB self-assembles above its
14 critical micelle concentration (CMC = 0.15 mM) into small spherical micelles as
15 determined by complementary scattering techniques. This surfactant readily interacts
16 with the supercoiled plasmid DNA pBR322 *via* electrostatics and hydrophobic
17 interactions. Upon increasing surfactant concentration, successive phase transitions
18 are observed from partial neutralization to full compaction of DNA as evidenced by
19 agarose gel electrophoresis, tensiometry, pyrene fluorescence, UV-Vis absorbance
20 and circular dichroism measurements. Under UVA radiation ($\lambda \geq 335$ nm), we show
21 that the presence of the surfactant increases photooxidized damage on DNA

22 especially in the compacted state. A mechanistic study using selective scavengers
23 shows the involvement of singlet oxygen in these oxidative processes due to the
24 direct UVA absorption of DNA itself.

25

26 **Keywords**

27 surfactant; self-assembly; DNA; formulation; UVA photosensitization

28

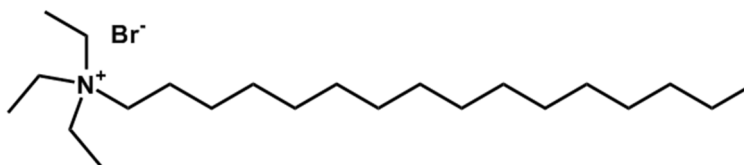
29 **corresponding author: Dr. Christophe Déjugnat, dejugnat@chimie.ups-tlse.fr*

30 **1. Introduction**

31 If gene therapy opens up new therapeutic perspectives in the treatment of
32 inherited deficiency diseases (*e. g.* cystic fibrosis), acquired diseases (cancer,
33 neurodegenerative diseases) or infectious diseases (hepatitis, AIDS), its success
34 depends on the effective transmission and expression of genetic material within cells.
35 This undoubtedly requires the development of systems capable of efficiently and
36 safely crossing biological barriers on the way to the nucleus and transmitting the drug
37 gene there. Most of the systems used involve recombinant viral vectors, capable of
38 inserting efficiently the transgene into the cells. Although the latter are very effective
39 in the transfer function, their use has a number of disadvantages (production cost,
40 safety, development of immune reactions, and risk of pathogenicity). To avoid them,
41 a number of synthetic vectors have been developed. They are mostly cationic
42 derivatives of a lipidic or polymeric nature capable of interacting with DNA by
43 electrostatic interactions and compacting it to form particles (aggregates).¹ Moreover,
44 since the effective charge of the DNA and its size are reduced, the efficiency of the
45 transfer of the drug gene to its site of action is also improved.

46 In the case of the *in vivo* delivery, the compacted gene/vector system can be
47 transferred to the target DNA in two ways: either by the systemic route or by local
48 application.² However, whatever the mode of administration, the gene must be
49 associated with a system capable of protecting it against aggression by the external
50 environment and in particular from UV radiation, one of the main sources of DNA
51 damage at the origin of photocarcinogenesis processes. While the photomutagenic
52 potential of UVB radiation has long been established, that of UVA radiation, which is
53 longer and deeper penetrating the skin, has only recently been recognized. Indeed,
54 the direct formation of cyclobutane pyrimidine dimers (CPD) in DNA under UVA

55 radiation has been widely reported³⁻¹² and the involvement of UVA radiation in
56 cancer and skin aging processes is now well established. However, no study has
57 been carried out on the direct influence of UVA radiation on DNA in a synthetic vector
58 system. Yet DNA delivery in the skin could be affected by sunlight. The studies
59 carried out in this sense involved the presence of a photosensitizer and focused on
60 studying the influence of the formulation on the formation of photoinduced oxidized
61 damage¹³ while the direct absorption of UVA radiation by DNA has been widely
62 demonstrated. So, the purpose of this work is to focus on the direct formation of
63 oxidized lesions on DNA formulations under UVA radiation involving as cationic
64 derivatives, a close analog of cetyltrimethylammonium bromide (CTAB), namely
65 cetyltriethylammonium bromide (CTEAB, Figure 1).



66

67

68 **Figure 1. Structure of cetyltriethylammonium bromide (CTEAB).**

69

70 This cationic surfactant presents the advantage of being readily soluble in liquid
71 water at any temperature ($T_{Krafft} < 0\text{ }^{\circ}\text{C}$),¹⁴ whereas the Krafft temperature of CTAB
72 ($T_{Krafft} = 25\text{ }^{\circ}\text{C}$)¹⁴ could be the source of troubles when handling it at room
73 temperature (close to the solubility temperature). On the other hand, CTEAB
74 presents a bulkier head group than CTAB and this affects its self-organization
75 properties in pure water due to molecular packing considerations.¹⁵ For example,
76 although they have similar critical micelle concentrations (CMCs) in water, CTAB

77 forms elongated micelles while CTEAB rather self-assembles into much smaller,
78 slightly ellipsoidal micelles.^{16,17} Therefore CTEAB has been mainly used as pore
79 directing agent for the preparation of mesoporous materials thanks to its ability to
80 form micellar cubic phases,^{18–20} but also as adjuvant in enhancing oil recovery
81 technique.^{21,22} However its interaction with DNA has not been reported yet (few
82 authors sometimes describe the use of cetyltriethylammonium bromide in DNA
83 extraction and purification processes, but a closer look shows that it was a
84 misspelling of cetyltrimethylammonium bromide, which is widely used for decades in
85 reference protocols). Therefore, it is interesting to consider this CTEAB-DNA
86 formulation and to see whether the slight structural change (ethyl vs methyl) due to
87 the replacement of CTAB by CTEAB could induce significant changes or not.

88 In a first part we present the self-organization properties of CTEAB in the buffer
89 solution used as solvent for DNA. Indeed, aggregation of CTEAB has been depicted
90 in water but the presence of electrolytes (buffer) is known to have an impact on such
91 properties.²³ Therefore the determination of the CMC (by tensiometry and pyrene
92 fluorimetry) and the depiction of the micelles (by scattering experiments) will be
93 carried out. Then the CTEAB-DNA interactions will be characterized to check that
94 CTEAB can also be used to formulate DNA, as an analog of CTAB. For that, the
95 critical aggregation concentrations (CACs) will be determined by complementary
96 techniques (tensiometry, pyrene fluorimetry, agarose gel electrophoresis, UV-Vis
97 absorbance and circular dichroism measurements). Finally, we will investigate the
98 effects of UVA radiation on these formulations (by agarose gel electrophoresis) and
99 will evidence that it can lead to direct DNA photosensitization. Experiments conducted
100 in the presence of peculiar scavengers will allow a mechanistic interpretation of the
101 results obtained.

2. Materials and methods

2.1. Materials

Triethylamine (purity 99.9 %) and 1-bromohexadecane (purity 98%) were purchased from VWR (Fontenay Sous Bois, France) and Lancaster (Morecambe, England), respectively. CTEAB was synthesized as described in the literature²⁴ and purification protocol was improved. Briefly, 1-bromohexadecane (20 g, 65 mmol) was reacted with triethylamine (10 mL, 72 mmol) in 130 mL absolute ethanol for 72 h at 85 °C (reflux). After evaporation to dryness under reduced pressure, the residue was dissolved in chloroform and ethyl acetate was added to induce precipitation. After precipitation was completed at 4 °C, the white solid was collected by filtration and washed with ethyl acetate. Final purification was achieved by solid phase extraction (SPE) on a reverse phase Chromabond C₁₈ ec chromatographic column (70 mL, 10 g) from Macherey-Nagel (first washing with water then elution with methanol). This step ensured full removal of the impurity trimethylamine hydrobromide. Evaporation of methanol afforded CTEAB as a white crystalline solid. Purity was assessed by nuclear magnetic resonance (NMR) and high-resolution mass spectroscopy (HRMS). (see *Supporting Information*).

Tris(hydroxymethyl)aminomethane (TRIS, purity 99.8 %) was from Fisher Scientific (Geel, Belgium). Supercoiled plasmid DNA (Form I) pBR322 (4361 base pairs) was purchased from Thermo Fisher Scientific (Vilnius, Lithuania), stored in 10×10^{-3} mol.L⁻¹ of TRIS/HCL (pH 7.6) and 1×10^{-3} mol.L⁻¹ of EDTA. The DNA was used after dilution in a 20 mM TRIS/HCl buffer (pH=7.4) to obtain a stock solution at $[\text{DNA-PO}_4] = 4.5 \times 10^{-4}$ mol.L⁻¹. All the DNA concentration indicated on the manuscript are in mol phosphate.L⁻¹. Heparin sodium salt (purity 99.8%) was purchased from Alfa Aesar (Heysham, Germany) and Sodium azide (NaN₃, purity 99%) from Alfa Aesar

127 (Karlsruhe, Germany). Agarose and tert-butanol ($t\text{BuOH}$, purity 99.5%) were obtained
128 from Sigma-Aldrich (Saint Louis, USA), while pyrene (purity 98%) was from Acros
129 Organics (Geel, Belgium). Ethidium Bromide (EB) was purchased as a $10\text{ mg}\cdot\text{mL}^{-1}$
130 aqueous solution from Invitrogen (Carlsbad, USA). D_2O (purity 99.9%) was obtained
131 from Eurisotop (Saint Aubin, France) and T4 endonuclease V (pyrimidine dimer
132 glycosylase) from BioLabs (New England, USA). Bromophenol blue was purchased
133 from Sigma Aldrich (Saint Louis, USA).
134 Water used in all experiments was produced by a two-stage Milli-Q filtration system
135 from Millipore and had a resistivity higher than $18.2\text{ M}\Omega\cdot\text{cm}$.

136 **2.2. Surface tension measurements**

137 Surface tension measurements were performed using a Krüss EasyDyne tensiometer
138 using the Wilhelmy plate method. Temperatures were maintained at $25\text{ }^\circ\text{C}$ ($\pm 0.1\text{ }^\circ\text{C}$)
139 by circulating thermostated water through a jacketed vessel containing the solution.
140 For each experiment, surface tension was measured three times (each time ten
141 readings were performed and averaged) after an equilibration time of 30 minutes.

142 **2.3. Fluorescence measurements**

143 A stock solution of pyrene ($10^{-4}\text{ mol}\cdot\text{L}^{-1}$), was prepared in methanol and stored in
144 glass vials at $4\text{ }^\circ\text{C}$. The solutions for fluorescence probing studies were prepared by
145 adding $1\text{ }\mu\text{L}$ of this pyrene stock solution ($10^{-4}\text{ mol}\cdot\text{L}^{-1}$) to $399\text{ }\mu\text{L}$ of the sample
146 solution. Final concentration of pyrene was $2.5\times 10^{-7}\text{ mol}\cdot\text{L}^{-1}$, while the amount of
147 methanol remained very low ($0.25\text{ }\%$ vol.) Fluorescence measurements were
148 performed on a Fluorolog Horiba spectrofluorimeter equipped with channel multiple
149 tau correlator (auto and cross correlation, 1088 real time channels) and a

150 thermostated cuvette holder at 25 ± 0.1 °C. Excitation wavelength was 335 nm, and
151 the fluorescence emission was recorded between 350 and 500 nm.

152 **2.4. UV-Visible absorbance and circular dichroism measurements**

153 Absorption spectra were recorded on a Hewlett Packard HP 8452A Diode Array
154 Spectrophotometer with an optical path length of 1 cm.

155 Circular dichroism spectra were obtained from a circular dichroism spectrometer J-
156 815 from Jasco equipped with a 150 W Xenon arc lamp light source, using a
157 bandwidth of 0.5 nm, with medium sensitivity with a maximum of 200 mdeg. Data
158 acquisition was done in continuous mode.

159 **2.5. Multi-angle light scattering experiments**

160 The multi-angle light scattering (MALS) measurements were performed on a 3D LS
161 Spectrometer from LS Instruments (Fribourg, Switzerland) equipped with a 100 mW
162 high performance DPSS Laser (Cobolt) operating at $\lambda = 660$ nm, a two-channel
163 multiple tau correlator (auto and cross correlation, 1088 real time channels), a 3D
164 cross-correlation module, a variable-angle detection system, two high sensitivity APD
165 detectors, an automated laser attenuation system combined with on-line laser
166 intensity measurement, a temperature controllable sample chamber with index
167 matching vat, and an external circulator for temperature control (Julabo CF31).

168 Before analysis (and otherwise stated), samples were filtered through 0.2 μm
169 hydrophilic PTFE filters into the cylindrical scattering cells.

170 Measurements were performed at 25°C for scattering angles θ ranging from 12° to
171 150°, corresponding to scattering wave vectors q in the range from 2.7×10^{-3} to
172 2.4×10^{-2} nm^{-1} . As CTEAB solutions did not produce multiple scattering, the 3D-cross

173 correlation configuration was not required and the measurement were performed in
174 the classical 2D-pseudo cross configuration.

175 At each angle, 3 to 10 measurements were carried out and later averaged after
176 having discarded eventual meaningless correlograms. Analysis of both dynamic and
177 static light scattering measurements were performed using the home-made MULTI-
178 STORMS software developed by Dr. C. Mingotaud (see *Supporting Information*).

179 **2.6. Small-Angle X-ray Scattering experiments**

180 SAXS (Small-Angle X-ray Scattering measurements) were conducted at the
181 European Synchrotron Radiation Facility (ESRF, Grenoble, France) at the ID02
182 beamline. CTEAB solutions (5 to 20 mM) were transferred into glass capillaries
183 before measurements. The sample-to-detector distance was 2.5 m. Using 1 Å X-ray
184 wavelength, the q range covered was $2.9 \times 10^{-3} \text{ \AA}^{-1} < q < 3.1 \times 10^{-1} \text{ \AA}^{-1}$. For each
185 solution, 10 scans were recorded and averaged. For each scan, exposure time was
186 kept as low as 100 ms to prevent from radiation damage. The observed intensities
187 $I(q)$ were corrected for transmission, solvent, and detector response. The analysis of
188 the $I(q)$ profiles was performed using the SasView software
189 (<http://www.sasview.org/>).

190 **2.7. Irradiation experiments**

191 DNA irradiation was made with a Mercury Xenon lamp (Oriel instruments, 500W)
192 equipped with a long pass filter $\lambda \geq 335\text{nm}$ (Newport 20CGA-335 GC505) at 20°C.

193 The irradiated and non-irradiated sample volume was 100 μL . The final
194 concentrations in TRIS/HCl buffer (20 mM, pH=7.4) were $9 \times 10^{-5} \text{ mol phosphate} \cdot \text{L}^{-1}$
195 for the plasmid DNA pBR322, from 0 to $4 \times 10^{-3} \text{ mol} \cdot \text{L}^{-1}$ for the CTEAB solutions,

196 $200 \times 10^{-3} \text{ mol L}^{-1}$ for NaN_3 and 4% v/v for $t\text{BuOH}$. Each experiment was at least
197 triplicated.

198

199 **2.8. Agarose gel electrophoresis**

200 2.8.1. Sample preparation

201 50 μL of the sample solution were used on the T4 endonuclease V experiment. It
202 consists to add 10 μL of T4 endonuclease V (10000U/ml) and to incubate the solution
203 30 minutes at 37°C . 5 μL of bromophenol blue solution and 10 μL of Heparin 20%
204 (w/w in TRIS/ HCl buffer (20 mM, pH= 7.4) were added.

205 To the samples without T4 endonuclease V treatment, 5 μL of bromophenol blue
206 solution, 10 μL of Heparin 20% (w/w in TRIS/ HCl buffer) and 10 μL TRIS/ HCl buffer
207 (20 mM, pH= 7.4) were added.

208 2.8.2 Electrophoresis and photodensitometry

209 An aliquot of 40 μL of each sample was deposited into 0.8% agarose gel containing
210 0.02 % of Ethidium Bromide. Electrophoresis migration was carried out for 4 hours
211 under a constant electric field of 80 mV.

212 Single strand breaks (SSB) were quantified by photodensitometry using the ImageJ
213 software. To correct the lower efficiency of ethidium bromide binding to Form I DNA
214 with respect to Form II, a coefficient of 1.66 was used.²⁵

215

216

3. Results and discussion

217

3.1. Self-organization of CTEAB in TRIS/HCl buffer

218 CTEAB surfactant (Figure 1) was synthesized as described in the literature²⁴ and

219 dissolved in 20 mM TRIS/HCl buffer solutions at pH = 7.4. Determination of the CMC

220 by tensiometry was performed by measuring the variation of the surface tension as a

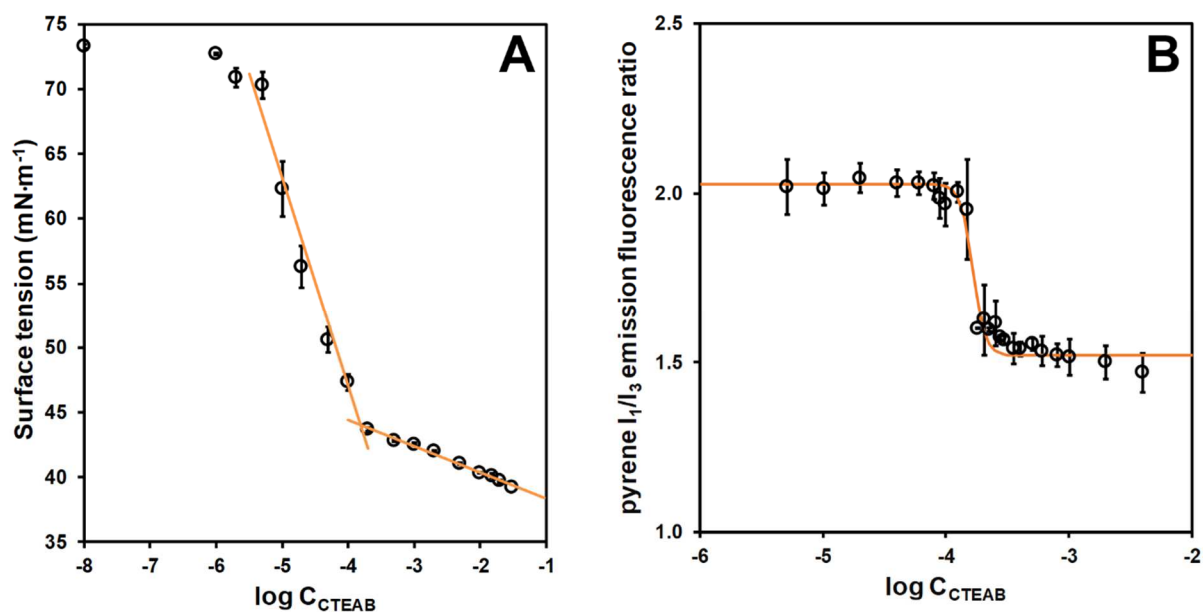
221 function of the surfactant concentration. In the dilute regime, the surface tension

222 value is close to the one of water and then it decreases when the concentration of

223 surfactant increases. At the threshold value which corresponds to the CMC, the

224 surface tension does not vary much upon increasing surfactant concentration (Figure

225 2A).



226

227 **Figure 2. Variation of the surface tension (A) and of the pyrene I₁/I₃**
228 **fluorescence emission ratio (B) of CTEAB solutions as a function of the CTEAB**
229 **concentration in 20 mM TRIS/HCl buffer (pH = 7.4) at 25 °C.**

230

231 By this technique the CMC of CTEAB was found to be $1.5 (\pm 0.2) \times 10^{-4} \text{ mol}\cdot\text{L}^{-1}$ in the

232 20 mM TRIS/HCl buffer (pH = 7.4) at 25 °C. This value is much lower than the CMC

233 values reported in the literature for CTEAB in water: $7-8 \times 10^{-4} \text{ mol} \cdot \text{L}^{-1}$, as determined
 234 from tensiometry and conductivity experiments.^{16,17,26–29} This decrease of CMC
 235 means that the aggregation is favored in TRIS/HCl buffer compared to pure water.
 236 The effect of the electrolyte is to partially screen the repulsion electrostatic
 237 interactions between the similar charged head groups of the surfactant and therefore
 238 to promote aggregation. Thereby, the CMC is lowering by addition of electrolyte.
 239 In the same way, Haq, Z. and coworkers³⁰ reported a decrease of the CMC of the
 240 CTAB from $0.98 \text{ mol} \cdot \text{L}^{-1}$ (at 303 K) to $0.90 \text{ mol} \cdot \text{L}^{-1}$ at $3 \text{ mol} \cdot \text{L}^{-1}$ of NaCl, indicating the
 241 significant role of the electrostatic interactions between surfactant and electrolyte.

242 From the tensiometry curve, one can also estimate the minimal molecular cross-
 243 sectional area at the air/water interface $A_{s,min}$ at the CMC.²³ This is done using the
 244 Gibbs equation which relies the maximal surface excess concentration Γ_{max} to the
 245 slope of the surface tension vs log C curve before the CMC as follows:

$$\Gamma_{max} = -\frac{1}{2.303nRT} \cdot \frac{\partial \gamma}{\partial \log C} \quad (1)$$

246 where T is the temperature, R the gas constant, C the concentration, and n the
 247 number of adsorbed species (here $n = 2$, accounting for CTEA⁺ and Br⁻). Then $A_{s,min}$
 248 can be expressed as (2):

$$A_{s,min} = \frac{1}{N_A \Gamma_{max}} \quad (2)$$

249 where N_A is the Avogadro number. Applying this to the curve in Figure 2A gives
 250 $A_{s,min} = 110 (\pm 10) \text{ \AA}^2 \cdot \text{molecule}^{-1}$. This value is quite high compared to a surface of
 251 $62 \text{ \AA}^2 \cdot \text{molecule}^{-1}$ reported for CTEAB in pure water,²⁹ suggesting that the distance
 252 between the surfactants got increased at the interface in the presence of electrolytes.
 253 The fact that the interface occupation appears less compact (and the surfactants

254 bulkier) might be due to the accumulation of species (like water or ions) between the
255 surfactants.

256 The aggregation properties of CTEAB in TRIS/HCl buffer have also been
257 studied by pyrene fluorescence measurements. Pyrene is a hydrophobic fluorescent
258 probe that has been widely used for the characterization of self-assembling systems
259 due to the specific variation of its emission fluorescence as a function of the local
260 polarity.³¹ In its specific multi-peak emission spectrum, the I_1/I_3 intensity ratio between
261 the first and third peaks (I_1 at 372 nm and I_3 at 383 nm respectively) is decreasing if
262 the polarity decreases. In surfactant systems, this I_1/I_3 ratio varies as a function of the
263 surfactant concentration with a sharp decrease at the CMC, from a high value (below
264 CMC, pyrene located in water) to a lower one (above CMC, pyrene located in the
265 hydrophobic inner core of the micelles). The results regarding pyrene fluorescence as
266 a function of CTEAB concentration in TRIS/HCl buffer are represented in Figure 2B.
267 The variation of the I_1/I_3 ratio has been adjusted by a sigmoidal Boltzmann function to
268 determinate the CMC.³²

269 From this fluorescence measurements, the aggregation of CTEAB in TRIS/HCl
270 buffer occurs at $CMC = 1.6 (\pm 0.2) \times 10^{-4} \text{ mol}\cdot\text{L}^{-1}$, which is in good accordance with
271 tensiometry measurements (using this quick technique we also checked the CMC of
272 CTEAB in pure water and found $7.1 (\pm 0.2) \times 10^{-4} \text{ mol}\cdot\text{L}^{-1}$, which is very close to the
273 values reported in the literature,^{16,17,26–29} see *Supporting Information, Figure S3*). In
274 addition, the intrinsic value of the I_1/I_3 ratio is directly related to local micropolarity: a
275 low ratio value (<1) indicates that pyrene is surrounded by a nonpolar environment,
276 while higher ratio values (>1) show that the pyrene environment is polar.³¹ This ratio
277 has been shown to vary from about 0.6 in alkanes to 1.2-1.6 in alcohols and up to 1.9
278 in water.^{31,33} In the present case of CTEAB, we observed a decrease of the I_1/I_3 ratio

279 from 2.0 to 1.5 at the CMC. This shows that even when located in micelles, the
280 pyrene probe is still in a rather polar environment. This suggest that water molecules
281 have partially penetrated the inner micellar cores, leading to an increase of the I_1/I_3
282 ratio.^{31,34} This is directly related to the surfactants head groups: bulky heads induce
283 less compact interfaces and allow penetration of water, which is here consistent with
284 large polar surface areas determined for CTEAB from tensiometry measurements.

285 In order to get more insights on the structure of the aggregates formed by
286 CTEAB in aqueous TRIS/HCl solutions, both multi-angle static- and dynamic light
287 scattering (MASLS and MADLS) experiments were performed at different
288 concentrations ($[CTEAB] = 5$ to 30×10^{-3} mol·L⁻¹). Small angle X-Ray scattering
289 (SAXS) measurements were also carried out.

290 In light scattering experiments, the scattering wave vector q is defined as a function
291 of the scattering angle θ as described by equation (3).

$$q = \frac{4\pi n \sin(\theta/2)}{\lambda} \quad (3)$$

292 where n is the refractive index of the medium and λ the wavelength of the incident
293 light.

294 In MASLS, the excess of scattered intensity by a sample with respect to the
295 solvent is converted into absolute intensity (Rayleigh ratio R_θ , in cm⁻¹) using toluene
296 as a reference (see *Supporting Information*). Absolute Rayleigh excess ratios of
297 CTEAB solutions were measured in the 2.6×10^{-4} - 2.5×10^{-3} Å⁻¹ q range. In all cases,
298 flat plateaus were obtained meaning that the scattering was isotropic and that the
299 aggregates formed by CTEAB were very small in size (see *Supporting Information*,
300 *Figure S4*). As a consequence, the radius of gyration R_g could not be determined due
301 to the q -independent form factor in this q range. However, the variation of the
302 Rayleigh ratio as a function of the CTEAB concentration could allow Debye analysis

303 (see *Supporting Information, Figure S5*). Therefore, the apparent mass of the
 304 aggregates was determined to be $M_w = 41.1 \pm 1.6$ kDa. From this value and using the
 305 molar weight of CTEAB, it was possible to calculate the aggregation number (N_{agg})
 306 which was found to be $N_{agg} = 101 \pm 4$. This value is larger or equal to those reported
 307 for CTEAB in pure water ($N_{agg} = 49-100$),^{17,29} confirming that micellization in TRIS
 308 buffer is favored and allows a larger number of surfactant molecules to aggregate.

309 What is measured experimentally in MADLS is the autocorrelation function
 310 $g^{(2)}(q, \tau)$ of the scattered intensity $I(q, t)$, normalized over time (4):

$$g^{(2)}(q, \tau) = \frac{\langle I(q, t)I(q, t + \tau) \rangle}{\langle I(q, t) \rangle^2} \quad (4)$$

311 This latter is also related to the correlation function of the electric field $g^{(1)}(q, \tau)$ by
 312 the Siegert relationship (5):

$$g^{(2)}(q, \tau) = 1 + \beta |g^{(1)}(q, \tau)|^2 \quad \beta \leq 1 \quad (5)$$

313 For monodisperse spherical particles under Brownian motion, the autocorrelation
 314 function decays exponentially over time (6):

$$g^{(1)}(q, \tau) = e^{-\Gamma\tau} \quad (6)$$

315 where $\Gamma = D_0 q^2$ is the decay rate and D_0 is the translational diffusion coefficient of the
 316 particles. The hydrodynamic radius of equivalent sphere (R_h) is then obtained by the
 317 Stokes-Einstein relationship:

$$R_h = \frac{kT}{6\pi\eta D_0} \quad (7)$$

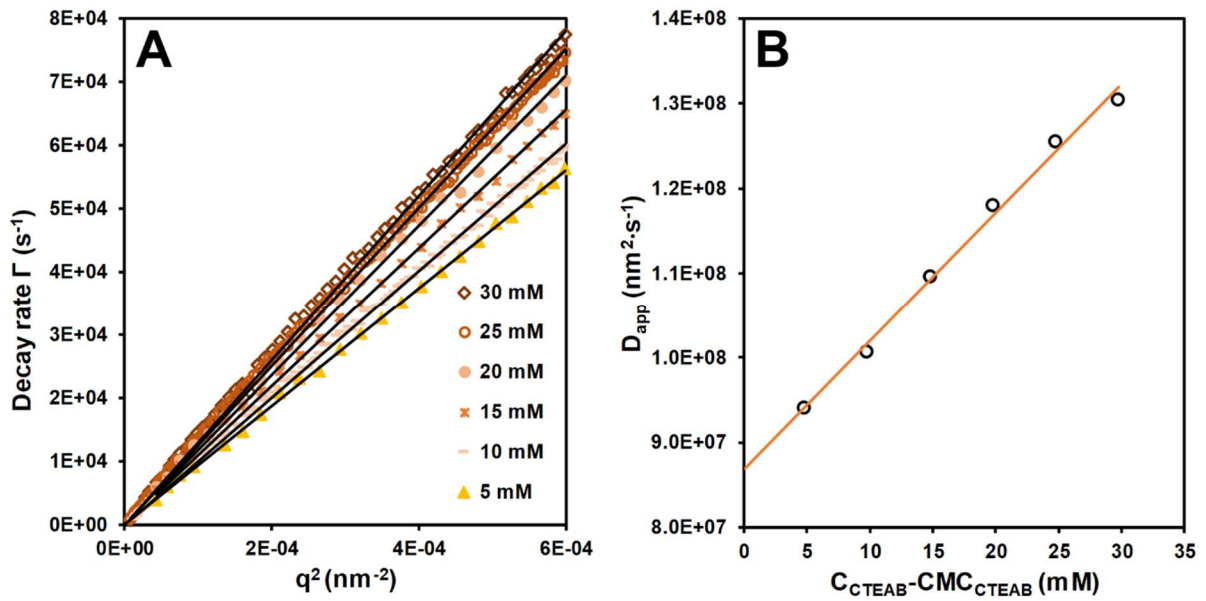
318 where k is the Boltzmann constant, T the absolute temperature, and η the solvent
 319 viscosity.

320 Experimentally, simple scattering was always observed (no multiple scattering) from
 321 the clear, transparent CTEAB solutions. In all cases, the autocorrelation functions
 322 were well fitted using a Cumulant analysis³⁵ (see *Supporting Information, Figure S6*),

323 affording the intensity-weighted decay rates Γ . Plotting decay rates as a function of q^2
 324 afforded linear profiles $\Gamma = D_{app}q^2$ (Figure 3A), meaning that single relaxation
 325 mechanisms were observed associated to single apparent translational diffusion
 326 coefficients (D_{app}).

327

328



329

330 **Figure 3. Linear variations of decay rates as a function of q^2 (A). Variation of the**
 331 **apparent diffusion coefficient D_{app} as a function of the micelle concentration**
 332 **(B).**

333

334 The apparent diffusion coefficients showed a linear dependence as a function of the
 335 micelle concentration (*ie* $C_{CTEAB} - CMC_{CTEAB}$) (Figure 3B):

$$D_{app} = D_0 + k(C_{CTEAB} - CMC_{CTEAB}) \quad (8)$$

336 This reflects inter-particle interactions (probably electrostatic repulsions between
 337 positively charged aggregates of cationic surfactants). Extrapolation at infinite dilution
 338 afforded $D_0 = 8.68 \times 10^7 \text{ nm}^2 \cdot \text{s}^{-1}$ and $R_{h,0} = 2.83 \text{ nm}$ from the Stokes-Einstein

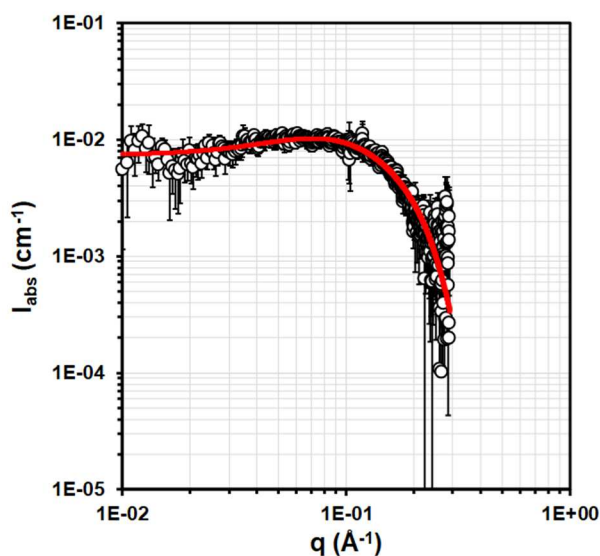
339 relationship. This hydrodynamic radius is comparable to the dimensions of micelles
340 formed by CTEAB in pure water.^{16,17}

341 Knowing the radius of the micelles, the determination of their surface gives
342 101 nm², and dividing it by the aggregation number, the surface occupied by one
343 surfactant head group is 1 nm², which is consistent with the surface estimated from
344 tensiometry measurements. It was also possible to determine the volume occupied
345 per surfactant at 0.94 nm³. The comparison of this value to the molecular volume of
346 CTEAB (0.64 nm³) indicates that about 10 water molecules are present around each
347 CTEAB molecule, confirming that CTEAB micelles are highly hydrated.

348 Complementary SAXS experiments were also carried out to get more
349 information on CTEAB micelles. The general expression of the scattered intensity
350 $I(q)$ is:

$$I(q) = \Phi \cdot V \cdot (\Delta\rho)^2 \cdot P(q) \cdot S(q) \quad (9)$$

351 where $q = [4\pi \sin(\theta/2)]/\lambda$ is the scattering vector (θ is the scattering angle), Φ is the
352 volume fraction of the scatterers, V is their volume, and $\Delta\rho$ is their difference in
353 scattering length density (SLD) with respect to the solvent. $P(q)$ is the scatterers'
354 form factor for which analytical expressions have been reported for various
355 geometries.^{36,37} $S(q)$ is the structure factor accounting for inter-particle interactions,
356 for which different models are also available.^{36,37} Regarding the CTEAB solutions, the
357 scattering intensities were very low, indicating a weak electronic contrast between the
358 solvent and the aggregates. Moreover, the profiles of the scattering curves suggested
359 a spherical shape for the aggregates, as illustrated in Figure 4 (full curves and fitting
360 parameters are reported in the *Supporting Information*).



361
 362 **Figure 4. SAXS profile of 20 mM CTEAB solution in 20 mM TRIS/HCl (pH = 7.4)**
 363 **at 25 °C. The solid line represents the adjustment of the data with a spherical**
 364 **form factor and a structure factor of a charged hard sphere.**

365
 366 Indeed, the data were efficiently adjusted using a $P(q)$ spherical model, whereas the
 367 ellipsoidal model used by others to describe CTEAB micelles in pure water was not
 368 convenient here.^{16,17} In addition, a structure factor $S(q)$ was included, which
 369 corresponded to a charged hard sphere model to take into account electrostatic
 370 repulsions between positively charged micelles (visible at low q as a decline of $I(q)$ in
 371 the SAXS curve). However, the classical core-shell structure could not be evidenced
 372 contrary to analogous cationic surfactants.³⁸ Instead, the SAXS profiles rather
 373 corresponded to small spherical shapes ($R = 14 \text{ \AA}$) with a scattering contrast that
 374 was the one of pure hydrophobic alkyl chains. This indicates that only a part of the
 375 inner core of the micelles could be observed by this technique, and it is again in
 376 accordance with a possible penetration of water towards the inner, “hydrophobic”
 377 core of the aggregates.

3.2. Interaction between CTEAB and DNA

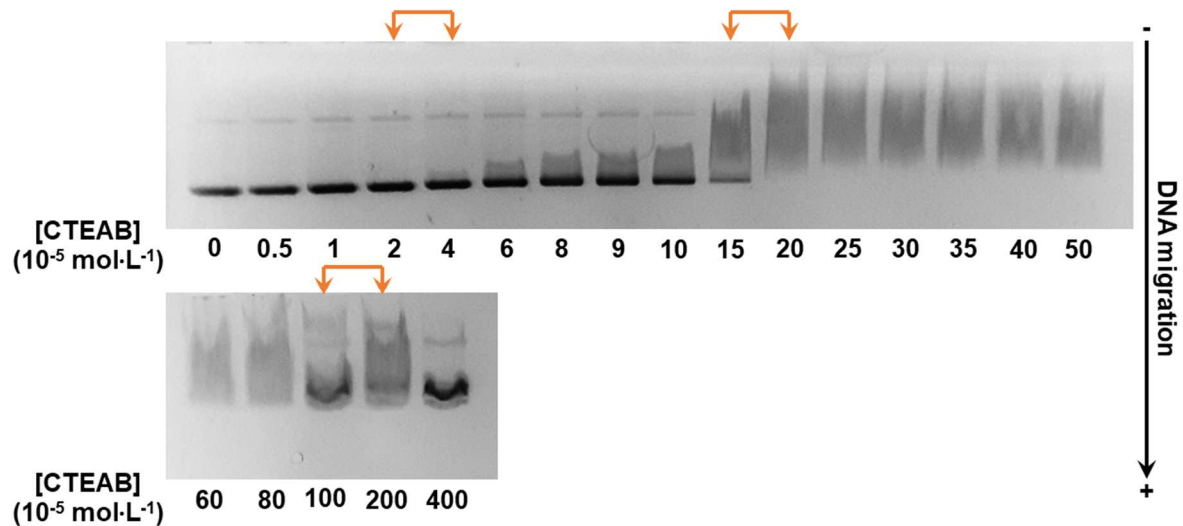
Cationic surfactants have been considered for a few decades as potential non-viral vectors for gene delivery, thanks to their ability to easily form complexes with DNA. This complexation induces the formation of highly organized assemblies, involving various intermolecular interactions (electrostatic, hydrophobic, etc.) and highly cooperative binding.^{39,40} In this field, CTAB was one of the most studied cationic surfactants. It has been shown that combination of electrostatic and hydrophobic interactions between CTAB and DNA induces functional and morphological changes of the biopolymer, particularly DNA compaction.⁴¹⁻⁵³ Considering CTEAB as a potential non-viral vector, it is therefore important to characterize the interactions occurring between the surfactant and the nucleic acid involved in such DNA formulations. It is especially interesting to study the effect of replacing CTAB by CTEAB on the different phase transitions, as we have shown that these structurally close surfactants differ, however, in their micellization properties.

Three macroscopic states were observed on CTEAB-DNA solutions depending on the CTEAB concentration. For $[\text{CTEAB}] < 20\text{-}30 \times 10^{-5} \text{ mol}\cdot\text{L}^{-1}$ clear solutions were observed. Between $20\text{-}30 \times 10^{-5} \text{ mol}\cdot\text{L}^{-1}$ and $100\text{-}200 \times 10^{-5} \text{ mol}\cdot\text{L}^{-1}$, turbid solutions appear. For higher CTEAB concentrations ($[\text{CTEAB}] > 100\text{-}200 \times 10^{-5} \text{ mol}\cdot\text{L}^{-1}$), turbid solutions turned to clear.

Therefore, complementary techniques (agarose gel electrophoresis, tensiometry, fluorimetry, UV-Visible spectrometry and circular dichroism) were used to study the binary system made of CTEAB and the supercoiled plasmid DNA pBR322 at various molar ratios.

401

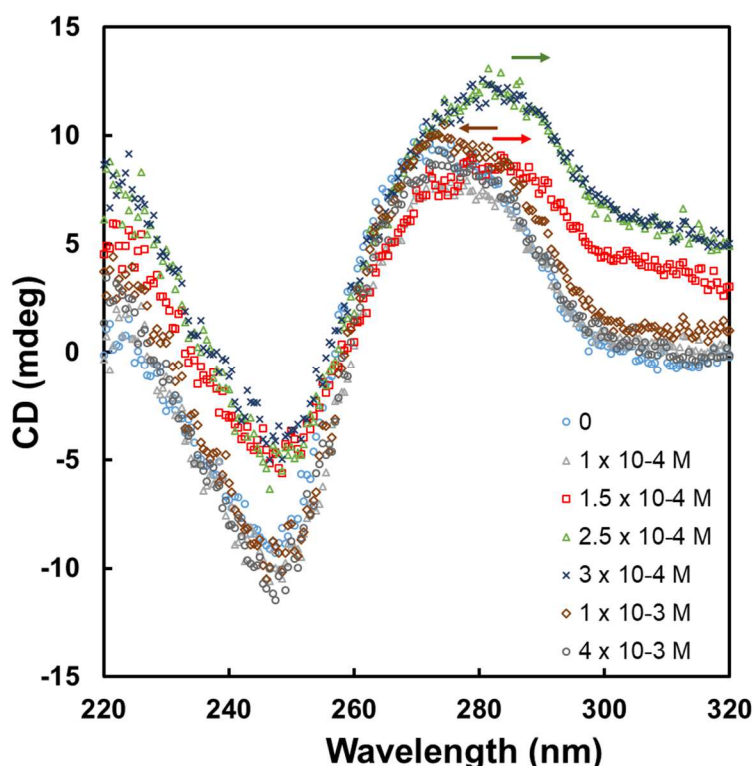
402 Agarose gel electrophoresis was first carried out to study CTEAB-DNA
 403 interactions with CTEAB concentrations ranging from 0 to $4 \times 10^{-3} \text{ mol}\cdot\text{L}^{-1}$ (Figure 5).



404 **Figure 5. Electrophoresis agarose gel of plasmid DNA in the presence of**
 405 **various CTEAB concentrations (DNA concentration was $[\text{DNA-PO}_4] = 9 \times 10^{-5}$**
 406 **$\text{mol}\cdot\text{L}^{-1}$). Orange arrows indicate phase transitions.**

407
 408 Analysis of the electrophoresis agarose gel indicates the existence of different
 409 CTEAB-DNA interactions. At low CTEAB concentration, below $4 \times 10^{-5} \text{ mol}\cdot\text{L}^{-1}$
 410 ($[\text{CTEAB}]/[\text{DNA}] = 0.44$), the cooperative binding between DNA and CTEAB only
 411 slightly impacts the DNA mobility. In the second region, for $2-4 \times 10^{-5} \text{ mol}\cdot\text{L}^{-1} <$
 412 $[\text{CTEAB}] < 15-20 \times 10^{-5} \text{ mol}\cdot\text{L}^{-1}$, ($0.44 < [\text{CTEAB}]/[\text{DNA}] < 2.2$) the complexation of
 413 CTEAB to DNA reduces the electrophoresis mobility of the DNA and a smear
 414 appears on the gel.¹³ This results from the formation of aggregates between DNA
 415 and CTEAB, leading to the gradual compaction of DNA. Above $15-20 \times 10^{-5} \text{ mol}\cdot\text{L}^{-1}$
 416 ($[\text{CTEAB}]/[\text{DNA}] = 2.2$), the CTEAB-DNA compaction seems complete as it is no
 417 longer possible to observe the initial DNA band on the agarose gel. The

418 corresponding solutions appear slightly turbid. For CTEAB concentrations above
419 $100 \times 10^{-5} \text{ mol} \cdot \text{L}^{-1}$ ($[\text{CTEAB}]/[\text{DNA}] = 11$), the electrophoretic mobility of DNA seems to
420 increase, with the re-appearance of a not-so-well defined band. This could indicate the
421 formation of another type of CTEAB-DNA complex in the presence of a large excess
422 of CTEAB and notably a decompaction process of DNA. In the literature, this
423 process was ascribed to the presence of an excess of the cationic surfactant, which
424 promotes the DNA decompaction.^{47,54,55} To go further into the understanding of the
425 interaction mechanisms between DNA and CTEAB, circular dichroism spectroscopy
426 (CD) was realized. The DNA circular dichroic spectrum exhibits two peaks. The first
427 one is a negative band at 245 nm, due to the helicity of DNA. The second one, at 278
428 nm is a positive band corresponding to the base stacking, as shown in Figure 6.⁵⁶⁻⁵⁹



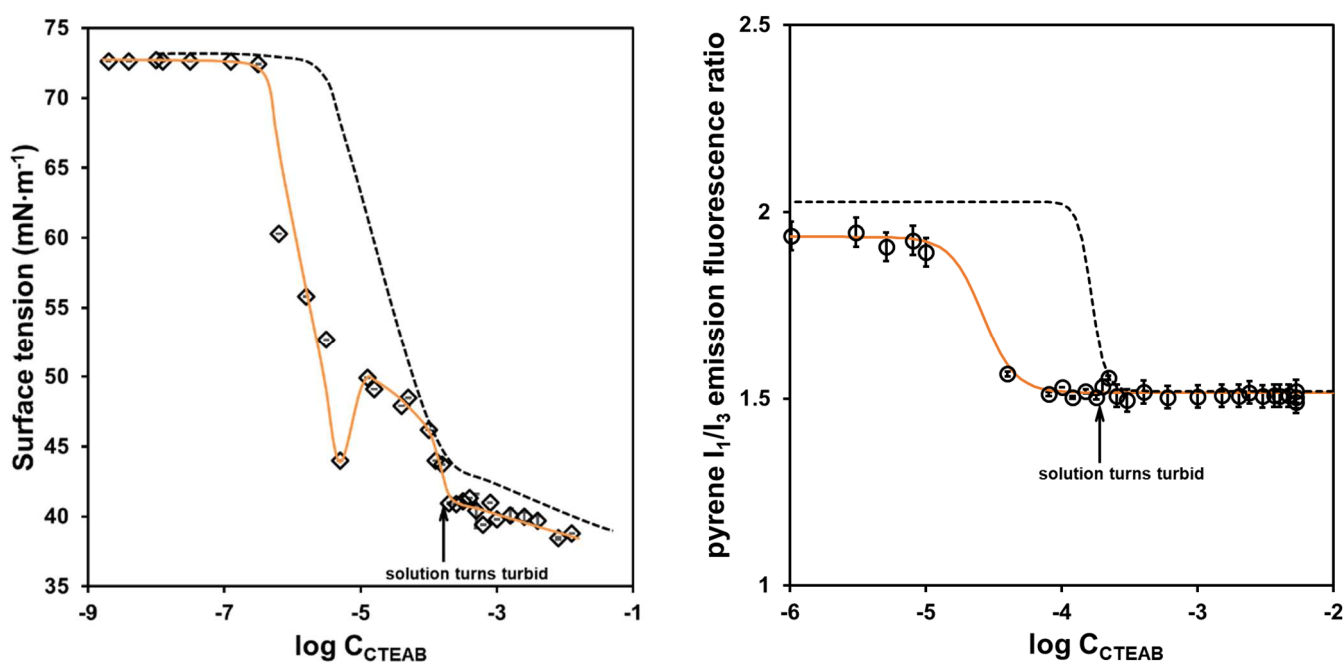
429
430 **Figure 6. Circular dichroism spectra in CTEAB-DNA solutions for various**
431 **CTEAB concentrations ($[\text{DNA-PO}_4^-] = 9 \times 10^{-5} \text{ mol} \cdot \text{L}^{-1}$, 20 mM TRIS/HCl buffer, pH**
432 **= 7.4) at 25 °C.**

433

434 The CTEAB-DNA complexes, in the two phase regions, present a red-shift of the
435 positive signal from 278 nm to 284 nm, for $[CTEAB] > 15 \times 10^{-5} \text{ mol.L}^{-1}$. This suggests
436 a minor changing of interactions between the DNA bases and the evidence of the
437 DNA compaction process in presence of CTEAB surfactant.⁵⁸ The observed
438 transition could be due by the reduction of the DNA hydration layer, caused by a
439 helical enhancement and a pitch shortening.^{58,59} With further CTEAB concentration
440 increase (from $100 \times 10^{-5} \text{ mol.L}^{-1}$), there is a blue shift of the positive band and the
441 position and intensity of that band recovers as DNA bands. It shows that CTEAB can
442 decompact DNA with excessive amount of surfactant as it was already described in
443 the literature for other surfactants.^{47,54,55} These two peculiar CTEAB concentrations
444 are on the same range that the ones find with the electrophoresis experiment.

445

446 CTEAB-DNA interactions were also evidenced by surface tension
447 measurements. Figure 7A shows the variation of the surface tension of the DNA
448 solution as a function of the CTEAB concentration.



449 **Figure 7. Variation of the surface tension (A), and of the pyrene I_1/I_3**
450 **fluorescence emission ratio (B) of CTEAB solutions as a function of CTEAB**
451 **concentration, in the presence of DNA ($[DNA-PO_4^-] = 9 \times 10^{-5} \text{ mol}\cdot\text{L}^{-1}$, 20 mM**
452 **TRIS/HCl buffer, pH = 7.4) at 25 °C. Dashed lines refer to CTEAB alone, for**
453 **comparison.**

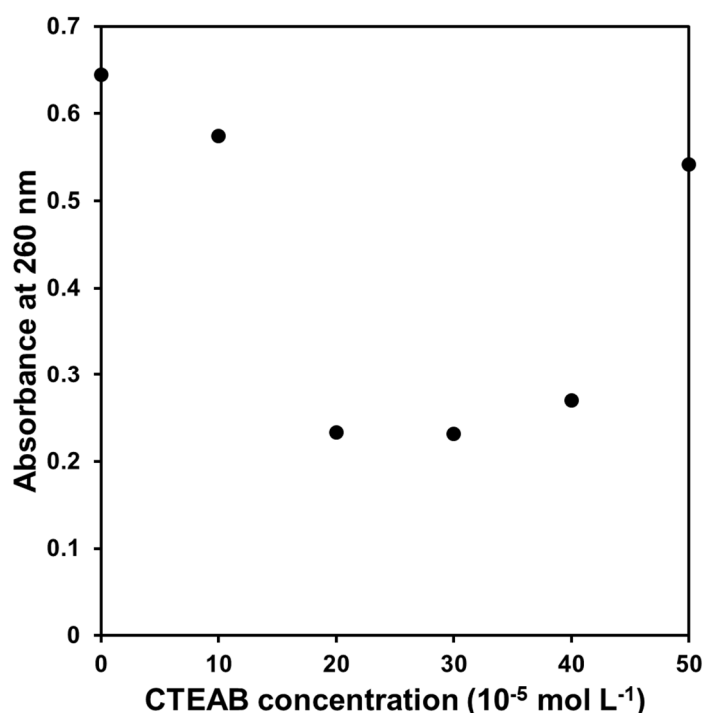
454

455 The curve profile obtained in the presence of DNA is more complex than the
456 one for surfactant alone. Indeed, surface tension started to decrease at very low
457 CTEAB concentrations ($< 10^{-6} \text{ mol}\cdot\text{L}^{-1}$) to reach a first minimum at $[CTEAB] =$
458 $0.16 \times 10^{-5} \text{ mol}\cdot\text{L}^{-1}$ ($[CTEAB]/[DNA] = 0.02$). It occurs well below the CMC of CTEAB,
459 meaning that this phenomenon does not correspond to the formation of micelles. This
460 rather shows the synergistic interaction between oppositely charged species that
461 leads to the formation of highly surface active CTEAB-DNA complexes located at the
462 air/water interface, as proposed by others.^{41,60–62} This complexation is driven both by
463 electrostatic interactions but also by hydrophobic interactions between the surfactant
464 and the biopolymer.⁴¹ In this concentration range, the CTEAB molecules are believed
465 to gradually decorate the DNA strand by progressive charge neutralization. Then,
466 upon increasing CTEAB concentration, the surface tension rises to a local maximum
467 and finally decreases again and reaches the curve of pure CTEAB. This could be
468 attributed to a partial desorption of the CTEAB-DNA complexes from the interface as
469 they accumulate in the bulk solution upon adsorption of further surfactant, potentially
470 forming new types of aggregates. Finally, the transition to a “plateau” coincides with
471 the apparition of a turbid solution and is observed at $[CTEAB] = 20 \times 10^{-5} \text{ mol}\cdot\text{L}^{-1}$
472 ($[CTEAB]/[DNA] = 2.2$). At this point the polyanion is saturated with surfactant and
473 the complex formed corresponds to formulated DNA. As the air/water interface is now

474 only occupied by surfactants, surface tension monitors then only the micellization of
475 CTEAB upon further addition of surfactant.

476 In a complementary way, pyrene fluorescence was studied at different
477 [CTEAB]/[DNA] ratios as previously conducted for CTEAB alone. In Figure 7B is
478 presented the variation of the pyrene I_1/I_3 emission fluorescence ratio as a function of
479 the CTEAB concentration in a DNA solution. We observed a classical sigmoidal
480 shape referring to a phase transition and the formation of hydrophobic domains.
481 Below the phase transition, the I_1/I_3 ratio was found to be 1.93 versus 2.03 in the
482 case of pure CTEAB. This slight decrease means that, even if pyrene is largely in
483 contact with water or in polar environment, it has found some more hydrophobic
484 places to locate. Indeed, it is known that pyrene can interact with DNA *via* partial
485 intercalation at the grooves.^{63,64} Then the phase transition occurred at [CTEAB] =
486 $2.8 \times 10^{-5} \text{ mol} \cdot \text{L}^{-1}$ ([CTEAB]/[DNA] = 0.31). This critical concentration is much lower
487 than the CMC of pure CTEAB and refers here to a critical aggregation concentration
488 (CAC) evidencing again the synergistic aggregation of CTEAB and DNA. This point is
489 believed to refer to the transition between a state where DNA is decorated by
490 individual surfactant molecules (neutralization phase) and a state where CTEAB
491 molecules form local hydrophobic domains on the DNA strand (compaction phase).
492 Pyrene can locate in these aggregates and the I_1/I_3 ratio drops to the 1.51 value,
493 which is almost identical to what observed with CTEAB alone (1.50). This means that
494 pyrene still remains in a quite hydrated environment like in the case of CTEAB
495 micelles, where bulky head groups allow penetration of water. Note that the limited
496 decrease of the pyrene I_1/I_3 ratio does not allow the detection of further transitions as
497 observed for other DNA-cationic surfactant systems.^{65,66} The steric hindrance of the
498 triethylammonium moiety could also explain why the transition occurs at a

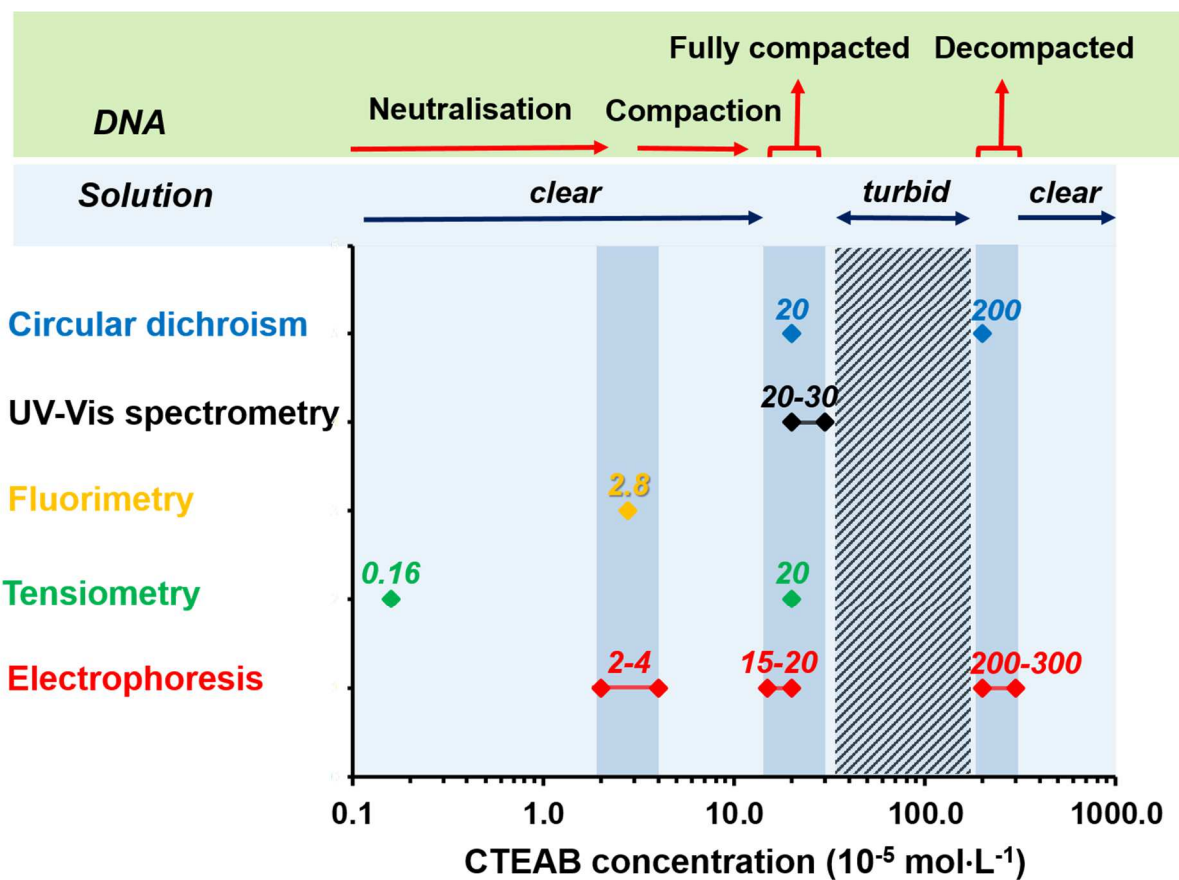
499 [CTEAB]/[DNA] ratio which is much lower than in the case of CTAB (0.31 vs. about
500 0.70)⁴⁸. Indeed, the neutralization phase is limited by the available space along the
501 DNA strand and depends on the size of the complexing cationic surfactant.
502 The effect of the surfactant on DNA compaction can also be followed by UV-Vis
503 spectrometry. Thus, DNA adsorption is performed at 260 nm for different CTEAB
504 concentrations (Figure 8). It can be observed that absorption of CTEAB-DNA
505 complex sharply decreases until a CTEAB concentration corresponding to $20\text{-}30 \times 10^{-5}$
506 $\text{mol}\cdot\text{L}^{-1}$. The increase in turbidity is due to strong electrostatic interactions between
507 the DNA and the surfactant. This result suggests that DNA is fully compacted.
508 CTEAB surfactant induces the reduction of the repulsive forces between the
509 phosphate groups of DNA leading to the formation of CTEAB-DNA aggregates.^{56,57}



510
511 **Figure 8. Variation of the absorbance of CTEAB-DNA solutions for various**
512 **CTEAB concentrations at 260 nm ($[\text{DNA-PO}_4] = 9 \times 10^{-5} \text{ mol}\cdot\text{L}^{-1}$, 20 mM TRIS/HCl**
513 **buffer, pH = 7.4) at 25 °C**

514

515 As the CTEAB concentration increases above $40 \times 10^{-5} \text{ mol}\cdot\text{L}^{-1}$, the absorbance value
 516 tends to recover to the origin value, ascribed to the decompaction process of DNA.
 517 The combination of these five complementary techniques has allowed to evidence
 518 different phase transitions for the CTEAB-DNA system depending on the surfactant
 519 concentration. They are summarized in Figure 9.
 520



521
 522 **Figure 9. CTEAB concentrations ($10^{-5} \text{ mol}\cdot\text{L}^{-1}$) at which different phase**
 523 **transitions were evidenced by five complementary techniques in the CTEAB-**
 524 **DNA system (DNA concentration was $[\text{DNA-PO}_4] = 9 \times 10^{-5} \text{ mol}\cdot\text{L}^{-1}$ in 20 mM**
 525 **TRIS/HCl, pH = 7.4) at 25 °C.**

526
 527 The first transition occurring at very low concentration has been highlighted by
 528 surface tension measurements, and corresponds to the neutralization

529 (“lipophilization”) of DNA by CTEAB. Next, agarose gel electrophoresis and
530 fluorimetry showed a phase transition towards a gradual compaction of DNA by
531 CTEAB. The end of this process, leading to a fully compacted DNA was evidenced
532 both by circular dichroism, UV-Vis spectroscopy, agarose gel electrophoresis and
533 surface tension measurements, as well as by macroscopic observations (solutions
534 became turbid). Finally, DNA decompaction was observed macroscopically and
535 highlighted by circular dichroism and agarose gel electrophoresis (DNA
536 redissolution).

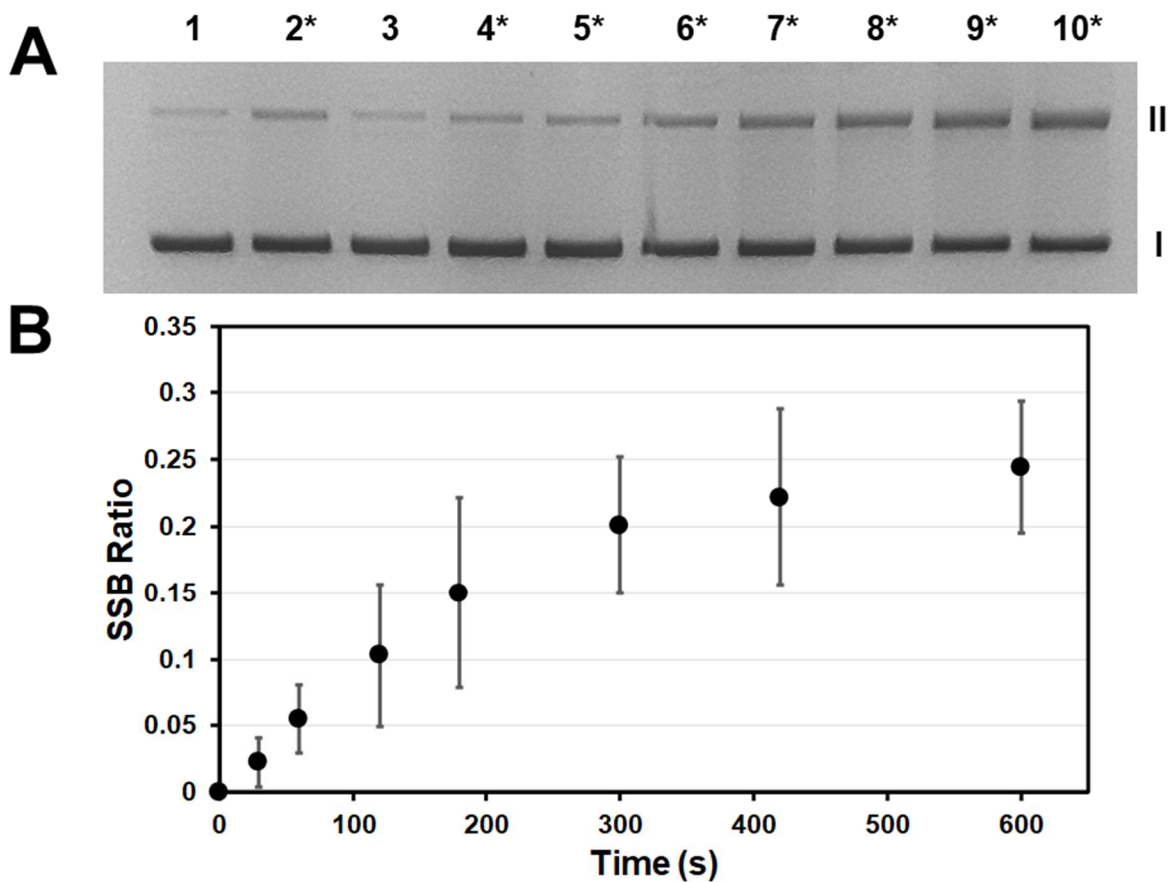
537 The formulation of DNA was then studied under UVA radiation, in order to evaluate
538 the influence of compaction on DNA photodamage formation.

539 **3.3. Photostability of formulated DNA under UVA radiation**

540 Supercoiled pBR322 plasmid DNA was used as a DNA model to study the effect
541 of CTEAB surfactant on DNA damage under UVA radiation ($\lambda \geq 335$ nm).
542 Photolesions such as single-strand breaks (SSB) damage can be easily revealed by
543 agarose gel electrophoresis. Indeed, conversion of pBR322 plasmid DNA from the
544 supercoiled form (or Form I) to the circular form (or Form II) gives two distinctive
545 bands that can be separated and visualized by agarose gel electrophoresis (further
546 noted as **I** and **II** on the gel pictures, respectively), and quantified by
547 photodensitometry.

548 A first study was performed to show the effect of the irradiation time on the DNA
549 damage in the presence of CTEAB. On figure 10A, electrophoresis agarose gel
550 shows the DNA damage for irradiation times varying from 30 seconds to 10 minutes.
551 A progressive increase of single strand breaks (SSB) was observed with the increase
552 of the irradiation time. The quantification of the SSB ratios by photodensitometry
553 (Figure 10B) shows a linear increase of the SSB ratio for the shortest irradiation

554 times and its slow-down after 200 seconds to reach a SSB ratio of about 0.25 for 10
555 min irradiation.



556

557 **Figure 10. DNA cleavage for different irradiation times at $\lambda \geq 335\text{nm}$ and 20°C (***
558 **indicate the irradiated samples). A: Electrophoresis agarose gel of plasmid**
559 **pBR322 ($9 \times 10^{-5} \text{ mol} \cdot \text{L}^{-1}$) with or without CTEAB ($5 \times 10^{-4} \text{ mol} \cdot \text{L}^{-1}$) in 20 mM**
560 **TRIS/HCl buffer (pH = 7.4). Lane 1: DNA, $t = 0 \text{ s}$; lane 2*: DNA, $t = 10 \text{ min}$; lanes**
561 **3* to 10*: DNA with CTEAB, $t = 0 \text{ s}$, 30 s, 1 min, 2 min, 3 min, 5 min, 7 min, and**
562 **10 min. B: Single strand break (SSB) ratio for different irradiation times as**
563 **quantified by photodensitometry.**

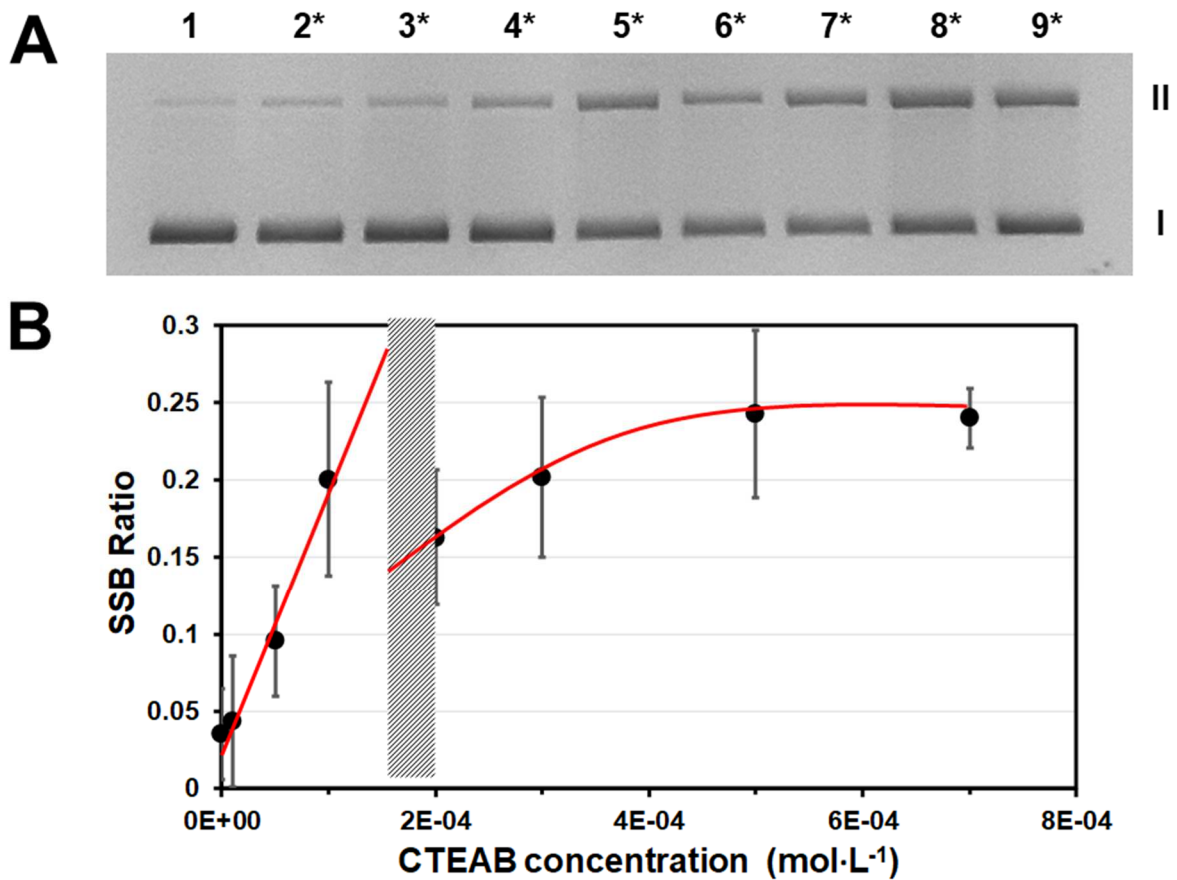
564

565 No longer time of irradiation was used because of the appearance of secondary DNA
566 strand breaks and the formation of pBR322 plasmid DNA linear form (data not show).

567 Control UVA irradiation of DNA alone also shows SSB damage that increase with
568 irradiation time, but twice less than in the lipoplex (see agarose gel and
569 photodensitometry quantification in the *Supporting Information*). DNA damage by
570 UVA light were already described in the literature and different hypothesis were made
571 to explain how DNA can be cleaved by UVA radiation whereas the nucleotides do not
572 absorb at these wavelengths.^{11,67-69} It has been shown that DNA solution presents a
573 slight and broad absorbance band in UVA range which could be enough to induce
574 UVA deterioration of DNA.^{11,67} Recently, Markovitsi implied the existence of
575 “collective” excited states in UVA photon absorption by DNA and speculated that
576 condensed DNA enhanced the collective character of electronic excitations.⁶⁹ The
577 CTEAB lipoplex made with the plasmid DNA pBR322 raises significantly the SSB
578 ratio. The effect of the compaction of DNA induced by CTEAB could explain the
579 increase of the DNA cleavage in the presence of surfactant. Indeed, Merindol *and al.*
580 have shown the appearance of an absorption band on UVA wavelengths when DNA
581 was aggregated by temperature.⁷⁰ To confirm this hypothesis, UV spectrum of the
582 CTEAB-DNA complex was performed (see *Supporting Information*): a UVA
583 absorption band appears in the presence of CTEAB. However, as the solution is
584 turbid, the light scattering produced by the colloidal dispersion of the lipoplexes
585 contributes to the UV-Vis spectrum and does not allow to differentiate the
586 absorbance of the lipoplex from the scattering and to quantify each contribution.

587
588 The effect of the CTEAB concentration on the DNA photodamage was also
589 studied and the irradiation time was fixed to 10 min. Indeed, this time allows to see
590 well the formation of SSB while avoiding overbreaks. The CTEAB concentration
591 range was from 0 to 7×10^{-4} mol·L⁻¹ and corresponds to the lanes 2* to 9* on the

592 electrophoresis agarose gel shown in figure 11A. In figure 11B, the enhancement of
593 the SSB ratio is shown with the increase of the CTEAB concentration.



594

595 **Figure 11. DNA cleavage for different CTEAB concentrations for 10 min**
596 **irradiation at $\lambda \geq 335$ nm and 20°C (* indicates the irradiated samples). A:**
597 **Electrophoresis agarose gel of plasmid pBR322 (9×10^{-5} mol·L⁻¹) in 20 mM**
598 **TRIS/HCl buffer (pH = 7.4). Lane 1: DNA alone without irradiation; lanes 2* to**
599 **10*: DNA with CTEAB irradiated, [CTEAB] = 0, 1×10^{-5} ; 5×10^{-5} ; 1×10^{-4} ; 2×10^{-4} ;**
600 **3×10^{-4} ; 5×10^{-4} ; 7×10^{-4} mol·L⁻¹. B: Single strand break (SSB) ratio for different**
601 **CTEAB concentrations.**

602

603 Two distinct behaviors may be highlighted. For [CTEAB] $\leq 1 \times 10^{-4}$ mol·L⁻¹, single-
604 strand breaks increase linearly with CTEAB concentration. Higher concentrations

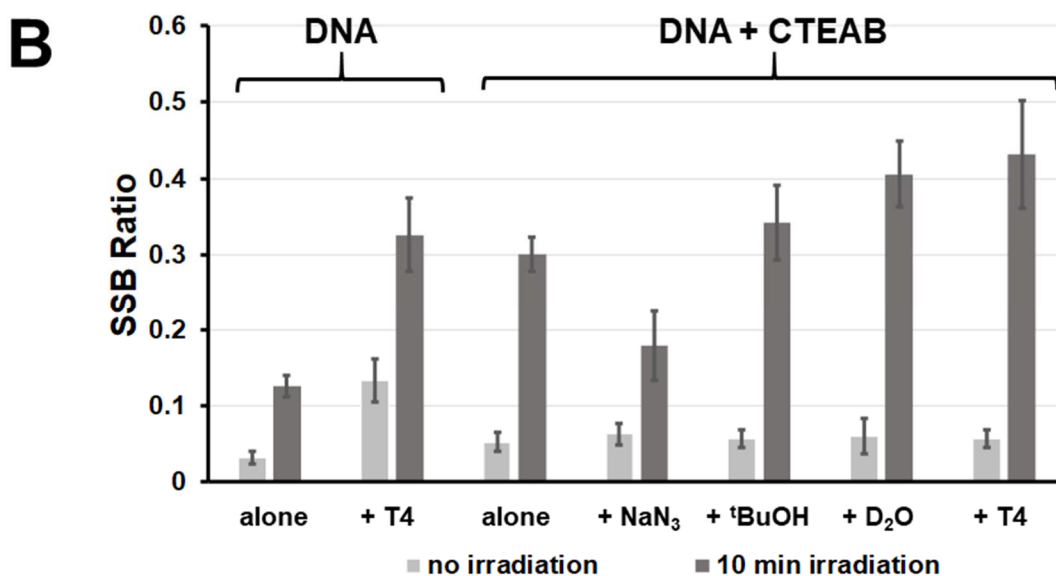
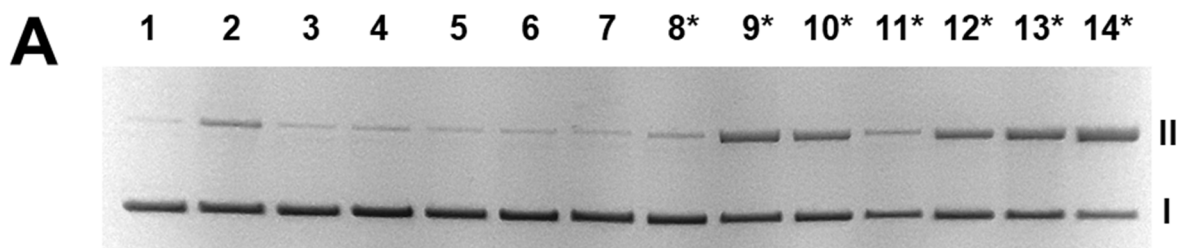
605 give rise to a second compartment which is not linear. The switch between these two
606 regimes occurs at the characteristic phase transition shown above and corresponding
607 to the full compaction of DNA by CTEAB.

608 Complementary experiments were undertaken to investigate the mechanism
609 involved on the DNA damage formed during UVA irradiation of the CTEAB-DNA
610 lipoplex.

611 One well-known damage induced by UVA irradiation of DNA is the formation of
612 cyclobutane pyrimidine dimer (CPD)^{11,71} and T4 endonuclease V is commonly used
613 to detect CPD in UV irradiated DNA. Indeed, the presence of CPD on the supercoiled
614 circular double-strand DNA induced a selective single-strand DNA scission by the
615 DNA repair enzyme. The plasmid circular form (Form II) appears and can be
616 revealed by agarose gel electrophoresis and quantified by photodensitometry as
617 shown in Figure 12. DNA alone was treated with the phage T4 endonuclease V
618 enzyme before and after 10 min of irradiation at $\lambda \geq 335$ nm (lanes 2 and 9*, Figure
619 12A). The enzymatic treatment reveals, by the AP-lyase activity of the T4
620 endonuclease V, the presence of abasic lesion on native plasmid DNA without
621 irradiation (lane 2). When the DNA is irradiated and treated with T4 endonuclease
622 (lane 9*), a significantly increase of the single-strand breaks is obtained. This is not
623 due to the formation of the CPD mediated by UVA radiation, but to the photooxidized
624 ones. Indeed, the SSB ratio with enzymatic treatment corresponds to the addition of
625 the native damage in DNA (lane 2) and the photooxidized damage of irradiated DNA
626 alone (lane 8*).

627 For the CTEAB-DNA lipoplex sample without irradiation and after T4 treatment (lane
628 7), the SSB ratio obtained is lower than DNA alone in the same condition (lane 2).
629 The abasic lesions present in native DNA seem to be no revealed by the T4 enzyme

630 in presence of CTEAB surfactant. It could be due to the quenching of the T4 enzyme
 631 activity by CTEAB itself or that the enzyme doesn't have access to the lesions
 632 present on the non-irradiated compacted CTEAB-DNA lipoplex. But when the
 633 CTEAB-DNA lipoplex is irradiated and treated with the T4 endonuclease (lane 14*),
 634 single strand breaks are obtained. As for DNA alone, the observed damage
 635 enhancement corresponds to the accumulation of the photooxidized damage due to
 636 the CTEAB-DNA irradiation (lane 10*) and the abasic native DNA lesions (lane 2). On
 637 the irradiated sample, the T4 enzyme seems to have access again to the DNA
 638 damage. Our hypothesis is that the enzyme doesn't have access to the DNA
 639 because of its compaction in the non-irradiated CTEAB-DNA complex and that the
 640 photodegradation of the CTEAB-DNA complex induces a partial decompaction,
 641 enough to give back DNA accessible to the T4 enzyme.



642

643 **Figure 12. DNA cleavage for 10 min of irradiation at $\lambda \geq 335\text{nm}$ and 20°C with**
644 **CTEAB ($5 \times 10^{-4} \text{ mol}\cdot\text{L}^{-1}$) and NaN_3 ($200 \times 10^{-3} \text{ mol}\cdot\text{L}^{-1}$), $^t\text{BuOH}$ (4% v/v), in D_2O (80%**
645 **v/v) or phage T4 endonuclease V treatment (T4) (* indicates the irradiated**
646 **samples). A: Electrophoresis agarose gel of plasmid pBR322 ($9 \times 10^{-5} \text{ mol}\cdot\text{L}^{-1}$) in**
647 **20 mM TRIS/HCl buffer (pH = 7.4). Lanes 1 and 8*: DNA alone; lanes 2 and 9*:**
648 **DNA + T4; lanes 3 and 10*: DNA + CTEAB; lanes 4 and 11*: DNA +CTEAB +**
649 **NaN_3 ; lanes 5 and 12*: DNA +CTEAB + $^t\text{BuOH}$; lanes 6 and 13*: DNA +CTEAB in**
650 **D_2O ; lanes 7 and 14*: DNA +CTEAB + T4. B: Single strand break (SSB) ratio of**
651 **CTEAB-DNA lipoplex $\pm \text{NaN}_3$, $^t\text{BuOH}$, D_2O or T4 with and without irradiation.**
652

653 To go further on the study of the mechanism involved in the formation of SSB,
654 peculiar scavengers have been used. CTEAB-DNA lipoplex was first irradiated in
655 presence of sodium azide NaN_3 (lane 11*), a well-known singlet oxygen quencher.⁷²
656 Under irradiation, the single-strand break ratio drops in presence of NaN_3 (Figure
657 12B). It means that the singlet oxygen is involved on the oxidized damage. To
658 confirm it, the CTEAB-DNA lipoplex solution was also prepared in D_2O TRIS/DCI
659 buffer and irradiated for 10 min (lane 13*). Indeed, D_2O increases the life time of the
660 singlet oxygen,^{73,74} and as expected an enhancement of SSB ratio is obtained (lane
661 13*). These results highlight the involvement of a type II mechanism by energy
662 transfer from the DNA molecule itself, acting as a chromophore,⁷⁵ to the ground state
663 of the molecular oxygen to produce the singlet oxygen responsible of these direct
664 oxidized photodamage under UVA radiation. Finally, the lipoplex irradiation was
665 performed with 4 % of tert-butanol ($^t\text{BuOH}$, lane 12*), as a OH radical scavenger.^{76,77}
666 No decrease of the SSB ratio is observable in the presence of $^t\text{BuOH}$ suggesting the

667 non-intervention of the type I mechanism involving hydroxyl radicals in these
668 processes.

669 In conclusion, UVA irradiation of DNA-CTEAB lipoplex induces the direct formation of
670 oxidized damage involving singlet oxygen and implementing energy transfer.
671 However, it does not lead to the formation of CPD. The compaction of the plasmid
672 pBR322 by the positive CTEAB surfactant is probably the cause of the increase in
673 photooxidized DNA damage.

674

675

676 **4. Conclusion**

677 Cationic surfactants or polymers have been shown to be efficient complexing agents
678 and transporters of DNA to cells. In this study, CTEAB surfactant was used to
679 complex a DNA model, the plasmid pBR322. The self-organization properties of the
680 CTEAB were studied by different physico-chemical characterizations (tensiometry,
681 pyrene fluorimetry and scattering experiments). Results show that CTEAB molecules
682 form small spherical and highly hydrated micelles in TRIS/HCl buffer solution. The
683 study of the interactions between CTEAB and plasmid DNA has highlighted different
684 phases, the DNA neutralization, the gradual until the full DNA compaction and the
685 decompaction process of DNA. Furthermore, formulated CTEAB-DNA lipoplexes
686 were irradiated under UVA light. With the increase of the irradiation time and of the
687 CTEAB concentration, an increase of DNA damage was observed. The involvement
688 of singlet oxygen has been shown to be responsible for these damage. The
689 compaction of DNA by CTEAB may be the cause of the increase in photooxidized
690 DNA damage. This study has investigated the DNA compaction by the cationic
691 surfactant CTEAB and pointed out its role on DNA photodamage under UVA
692 irradiation. Further work is currently under progress to show what could be the effect
693 of adding anti-oxidant drug such as vitamin E on the photodamage observed in this
694 system.

695

696 **Acknowledgements**

697 This work benefited from the use of the SasView application, originally developed
698 under NSF award DMR-0520547. SasView contains code developed with funding
699 from the European Union's Horizon 2020 research and innovation program under the
700 SINE2020 project, grant agreement No 654000. Dr. C. Mingotaud is thanked for help
701 in MULTI-STORMS use and for SAXS measurements.

702
703
704
705
706
707
708
709
710
711
712
713
714
715
716
717
718
719
720
721
722
723
724
725
726

References

- (1) Foldvari, M.; Chen, D. W.; Nafissi, N.; Calderon, D.; Narsineni, L.; Rafiee, A. Non-Viral Gene Therapy: Gains and Challenges of Non-Invasive Administration Methods. *J. Control. Release* **2016**, *240*, 165–190. <https://doi.org/10.1016/j.jconrel.2015.12.012>.
- (2) Dunbar, C. E.; High, K. A.; Joung, J. K.; Kohn, D. B.; Ozawa, K.; Sadelain, M. Gene Therapy Comes of Age. *Science (80-.)*. **2018**, *359*, eaan4672. <https://doi.org/10.1126/science.aan4672>.
- (3) Schuch, A. P.; Moreno, N. C.; Schuch, N. J.; Menck, C. F. M.; Garcia, C. C. M. Sunlight Damage to Cellular DNA: Focus on Oxidatively Generated Lesions. *Free Radic. Biol. Med.* **2017**, *107*, 110–124. <https://doi.org/10.1016/j.electacta.2018.01.181>.
- (4) Tyrrell, R. M. Induction of Pyrimidine Dimers in Bacterial DNA by 365 Nm Radiation. *Photochem. Photobiol.* **1973**, *17*, 69–73. <https://doi.org/10.1111/j.1751-1097.1973.tb06334.x>.
- (5) Kuluncsics, Z.; Perdiz, D.; Brulay, E.; Muel, B.; Sage, E. Wavelength Dependence of Ultraviolet-Induced DNA Damage Distribution : Involvement of Direct or Indirect Mechanisms and Possible Artefacts. *J. Photochem. Photobiol. B Biol.* **1999**, *49*, 71–80.
- (6) Perdiz, D.; Gróf, P.; Mezzina, M.; Nikaido, O.; Moustacchi, E.; Sage, E. Distribution and Repair of Bipyrimidine Photoproducts in Solar UV-Irradiated Mammalian Cells: Possible Role of Dewar Photoproducts in Solar Mutagenesis. *J. Biol. Chem.* **2000**, *275* (35), 26732–26742. <https://doi.org/10.1074/jbc.M001450200>.
- (7) Douki, T.; Reynaud-Angelin, A.; Cadet, J.; Sage, E. Bipyrimidine Photoproducts

- 727 Rather than Oxidative Lesions Are the Main Type of DNA Damage Involved in
728 the Genotoxic Effect of Solar UVA Radiation. *Biochemistry* **2003**, *42* (30),
729 9221–9226. <https://doi.org/10.1021/bi034593c>.
- 730 (8) Mouret, S.; Baudouin, C.; Charveron, M.; Favier, A.; Cadet, J.; Douki, T.
731 Cyclobutane Pyrimidine Dimers Are Predominant DNA Lesions in Whole
732 Human Skin Exposed to UVA Radiation. *Proc. Natl. Acad. Sci.* **2006**, *103* (37),
733 13765–13770. <https://doi.org/10.1073/pnas.0604213103>.
- 734 (9) Schuch, A. P.; da Silva Galhardo, R.; de Lima-Bessa, K. M.; Schuch, N. J.;
735 Menck, C. F. M. Development of a DNA-Dosimeter System for Monitoring the
736 Effects of Solar-Ultraviolet Radiation. *Photochem. Photobiol. Sci.* **2009**, *8*, 111–
737 120. <https://doi.org/10.1039/b810085c>.
- 738 (10) Jiang, Y.; Rabbi, M.; Kim, M.; Ke, C.; Lee, W.; Clark, R. L.; Mieczkowski, P. A.;
739 Marszalek, P. E. UVA Generates Pyrimidine Dimers in DNA Directly. *Biophys.*
740 *J.* **2009**, *96* (3), 1151–1158. <https://doi.org/10.1016/j.bpj.2008.10.030>.
- 741 (11) Mouret, S.; Philippe, C.; Gracia-Chantegrel, J.; Banyasz, A.; Karpati, S.;
742 Markovitsi, D.; Douki, T. UVA-Induced Cyclobutane Pyrimidine Dimers in DNA:
743 A Direct Photochemical Mechanism? *Org. Biomol. Chem.* **2010**, *8* (7), 1706–
744 1711. <https://doi.org/10.1039/b924712b>.
- 745 (12) Cortat, B.; Garcia, C. C. M.; Quinet, A.; Schuch, A. P.; De Lima-Bessa, K. M.;
746 Menck, C. F. M. The Relative Roles of DNA Damage Induced by UVA
747 Irradiation in Human Cells. *Photochem. Photobiol. Sci.* **2013**, *12* (8), 1483–
748 1495. <https://doi.org/10.1039/c3pp50023c>.
- 749 (13) Rudiuk, S.; Franceschi-Messant, S.; Chouini-Lalanne, N.; Perez, E.; Rico-
750 Lattes, I. Modulation of Photo-Oxidative DNA Damage by Cationic Surfactant
751 Complexation. *Langmuir* **2008**, *24* (16), 8452–8457.

- 752 <https://doi.org/10.1021/la800751k>.
- 753 (14) Davey, T. W.; Ducker, W. A.; Hayman, A. R.; Simpson, J. Krafft Temperature
754 Depression in Quaternary Ammonium Bromide Surfactants. *Langmuir* **1998**, *14*
755 (12), 3210–3213. <https://doi.org/10.1021/la9711894>.
- 756 (15) Israelachvili, J. N.; Mitchell, D. J.; Ninham, B. W. Theory of Self-Assembly of
757 Hydrocarbon Amphiphiles into Micelles and Bilayers. *J. Chem. Soc. Faraday*
758 *Trans. 2 Mol. Chem. Phys.* **1976**, 1525–1568.
759 <https://doi.org/10.1039/F29767201525>.
- 760 (16) Wasbrough, M. J.; Edler, K. J.; Hawley, A. M.; Holdaway, J. A.; Price, G. J.
761 Control of Mesosstructure in Self-Assembled Polymer/Surfactant Films by
762 Rational Micelle Design. *Soft Matter* **2012**, *8* (12), 3357–3362.
763 <https://doi.org/10.1039/c2sm07086c>.
- 764 (17) Jaber, R.; Wasbrough, M. J.; Holdaway, J. A.; Edler, K. J. Interactions between
765 Quaternary Ammonium Surfactants and Polyethylenimine at High PH in Film
766 Forming Systems. *J. Colloid Interface Sci.* **2015**, *449*, 286–296.
767 <https://doi.org/10.1016/j.jcis.2015.01.034>.
- 768 (18) Anderson, M. W.; Egger, C. C.; Tiddy, G. J. T.; Casci, J. L.; Brakke, K. A. A
769 New Minimal Surface and the Structure of Mesoporous Silicas. *Angew. Chemie*
770 *- Int. Ed.* **2005**, *44* (21), 3243–3248. <https://doi.org/10.1002/anie.200462295>.
- 771 (19) Kruk, M.; Jaroniec, M.; Sakamoto, Y.; Terasaki, O.; Ryoo, R.; Ko, C. H.
772 Determination of Pore Size and Pore Wall Structure of MCM-41 by Using
773 Nitrogen Adsorption, Transmission Electron Microscopy, and X-Ray Diffraction.
774 *J. Phys. Chem. B* **2000**, *104* (2), 292–301. <https://doi.org/10.1021/jp992718a>.
- 775 (20) Huo, Q.; Margolese, D. I.; Ciesla, U.; Feng, P.; Gier, T. E.; Sieger, P.; Leon, R.;
776 Petroff, P. M.; Schüth, F.; Stucky, G. D. Generalized Synthesis of Periodic

- 777 Surfactant/Inorganic Composite Materials. *Nature* **1994**, *368*, 317–321.
778 <https://doi.org/10.1038/368317a0>.
- 779 (21) Gou, S.; Yin, T.; Yan, L.; Guo, Q. Water-Soluble Complexes of Hydrophobically
780 Modified Polymer and Surface Active Imidazolium-Based Ionic Liquids for
781 Enhancing Oil Recovery. *Colloids Surfaces A Physicochem. Eng. Asp.* **2015**,
782 *471*, 45–53. <https://doi.org/10.1016/j.colsurfa.2015.02.022>.
- 783 (22) Li, X.; Xue, Q.; Wu, T.; Jin, Y.; Ling, C.; Lu, S. Oil Detachment from Silica
784 Surface Modified by Carboxy Groups in Aqueous Cetyltriethylammonium
785 Bromide Solution. *Appl. Surf. Sci.* **2015**, *353*, 1103–1111.
786 <https://doi.org/10.1016/j.apsusc.2015.07.014>.
- 787 (23) Rosen, M. J.; Kunjappu, J. . *Surfactants and Interfacial Phenomena, 3rd*
788 *Edition.*; 2012. <https://doi.org/10.1002/0471670561>.
- 789 (24) Kim, M. J.; Ryoo, R. Synthesis and Pore Size Control of Cubic Mesoporous
790 Silica SBA-1. *Chem. Mater.* **1999**, *11*, 487–491.
791 <https://doi.org/10.1021/cm980691m>.
- 792 (25) Ciulla, T. A.; Van Camp, J. R.; Resenfeld, A.; Kochevar, I. Photosensitization of
793 Single-Strand Breaks in PBR322 DNA by Rose Bengal. *Photochem.* **1989**, *49*
794 (3), 293–298.
- 795 (26) Soldi, V.; Keiper, J.; Romsted, L. S.; Cuccovia, I. M.; Chaimovich, H.
796 Arenediazonium Salts: New Probes of the Interfacial Compositions of
797 Association Colloids. 6. Relationships between Interfacial Counterion and
798 Water Concentrations and Surfactant Headgroup Size, Sphere-to-Rod
799 Transitions, and Chemical Reactivity in Cationic. *Langmuir* **2000**, *16*, 59–71.
800 <https://doi.org/10.1021/la990336q>.
- 801 (27) Bacaloglu, R.; Bunton, C. A.; Ortega, F. Micellar Enhancements of Rates of

- 802 SN2 Reactions of Halide Ions. The Effect of Headgroup Size. *J. Phys. Chem.*
803 **1989**, *93* (4), 1497–1502. <https://doi.org/10.1021/j100341a061>.
- 804 (28) Buckingham, S. A.; Garvey, C. J.; Warr, G. G. Effect of Head-Group Size on
805 Micellization and Phase Behavior in Quaternary Ammonium Surfactant
806 Systems. *J. Phys. Chem.* **1993**, *97* (39), 10236–10244.
807 <https://doi.org/10.1021/j100141a054>.
- 808 (29) Rodríguez, M. A.; Muñoz, M.; Graciani, M. del M.; Fernández Pachón, M. S.;
809 Moyá, M. L. Effects of Head Group Size on Micellization of
810 Cetyltrialkylammonium Bromide Surfactants in Water-Ethylene Glycol Mixtures.
811 *Colloids Surfaces A Physicochem. Eng. Asp.* **2007**, *298* (3), 177–185.
812 <https://doi.org/10.1016/j.colsurfa.2006.10.062>.
- 813 (30) Haq, Z. U.; Rehman, N.; Ali, F.; Khan, N. M.; Hidayat, U. Effect of Electrolyte (
814 NaCl) and Temperature on the Mechanism of Cetyl Trimethylammonium
815 Bromide Micelles. *Sains Malaysiana* **2017**, *46* (5), 733–741.
- 816 (31) Kalyanasundaram, K.; Thomas, J. K. Environmental Effects on Vibronic Band
817 Intensities in Pyrene Monomer Fluorescence and Their Application in Studies
818 of Micellar Systems. *J. Am. Chem. Soc.* **1977**, *99* (7), 2039–2044.
819 <https://doi.org/10.1021/ja00449a004>.
- 820 (32) Aguiar, J.; Carpena, P.; Molina-Bolívar, J. A.; Carnero Ruiz, C. On the
821 Determination of the Critical Micelle Concentration by the Pyrene 1:3 Ratio
822 Method. *J. Colloid Interface Sci.* **2003**, *258* (1), 116–122.
823 [https://doi.org/10.1016/S0021-9797\(02\)00082-6](https://doi.org/10.1016/S0021-9797(02)00082-6).
- 824 (33) Dong, D. C.; Winnik, M. A. The Py Scale of Solvent Polarities. *Canadian*
825 *Journal of Chemistry*. 1984, pp 2560–2565. <https://doi.org/10.1139/v84-437>.
- 826 (34) Lianos, P.; Lang, J.; Sturm, J.; Zana, R. Fluorescence-Probe Study of Oil-in-

- 827 Water Microemulsions. 3. Further Investigations Involving Other Surfactants
828 and Oil Mixtures. *J. Phys. Chem.* **1984**, *88* (4), 819–822.
829 <https://doi.org/10.1021/j150648a040>.
- 830 (35) Frisken, B. J. Revisiting the Method of Cumulants for the Analysis of Dynamic
831 Light-Scattering Data. *Appl. Opt.* **2001**, *40* (24), 4087–4091.
- 832 (36) Pedersen, J. S. Analysis of Small-Angle Scattering Data from Colloids and
833 Polymer Solutions: Modeling and Least-Squares Fitting. *Adv. Colloid Interface*
834 *Sci.* **1997**, *70* (1–3), 171–210. [https://doi.org/10.1016/S0001-8686\(97\)00312-6](https://doi.org/10.1016/S0001-8686(97)00312-6).
- 835 (37) Pedersen, J. S. Modelling of Small-Angle Scattering Data from Colloids and
836 Polymer Systems. In *Neutrons, X-rays and Light: Scattering Methods Applied*
837 *to Soft Condensed Matter*, 2002.
- 838 (38) Müller, W.; Déjugnat, C.; Zemb, T.; Dufreîche, J.-F.; Diat, O. How Do Anions
839 Affect Self-Assembly and Solubility of Cetylpyridinium Surfactants in Water. *J.*
840 *Phys. Chem. B* **2013**, *117* (5), 1345–1356. <https://doi.org/10.1021/jp3093622>.
- 841 (39) Liu, K.; Zheng, L.; Ma, C.; Göstl, R.; Herrmann, A. DNA-Surfactant Complexes:
842 Self-Assembly Properties and Applications. *Chem. Soc. Rev.* **2017**, *46*, 5147–
843 5172. <https://doi.org/10.1039/c7cs00165g>.
- 844 (40) Dias, R. S.; Pais, A. A. C. C.; Miguel, M. G.; Lindman, B. DNA and Surfactants
845 in Bulk and at Interfaces. *Colloids Surfaces A Physicochem. Eng. Asp.* **2004**,
846 *250*, 115–131. <https://doi.org/10.1016/j.colsurfa.2004.07.026>.
- 847 (41) Di Profio, P.; Germani, R.; Goracci, L.; Grilli, R.; Savelli, G.; Tiecco, M.
848 Interaction between DNA and Cationic Amphiphiles: A Multi-Technique Study.
849 *Langmuir* **2010**, *26* (11), 7885–7892. <https://doi.org/10.1021/la9047825>.
- 850 (42) Grueso, E.; Cerrillos, C.; Hidalgo, J.; Lopez-Cornejo, P. Compaction and
851 Decompaction of DNA Induced by the Cationic Surfactant CTAB. *Langmuir*

- 852 **2012**, *28* (30), 10968–10979. <https://doi.org/10.1021/la302373m>.
- 853 (43) Zhou, S.; Liang, D.; Burger, C.; Yeh, F.; Chu, B. Nanostructures of Complexes
854 Formed by Calf Thymus DNA Interacting with Cationic Surfactants.
855 *Biomacromolecules* **2004**, *5*, 1256–1261. <https://doi.org/10.1021/bm034524d>.
- 856 (44) Dias, R. S.; Innerlohinger, J.; Glatter, O.; Miguel, M. G.; Lindman, B. Coil-
857 Globule Transition of DNA Molecules Induced by Cationic Surfactants: A
858 Dynamic Light Scattering Study. *J. Phys. Chem. B* **2005**, *109*, 10458–10463.
859 <https://doi.org/10.1021/jp0444464>.
- 860 (45) Zhu, D.; Evans, R. K.; August, R. V.; Final, I.; January, F. Molecular Mechanism
861 and Thermodynamics Study of Plasmid DNA and Cationic Surfactants
862 Interactions. *Langmuir* **2006**, *22*, 3735–3743.
- 863 (46) Guo, Q.; Zhang, Z.; Song, Y.; Liu, S.; Gao, W.; Qiao, H.; Guo, L.; Wang, J.
864 Investigation on Interaction of DNA and Several Cationic Surfactants with
865 Different Head Groups by Spectroscopy, Gel Electrophoresis and Viscosity
866 Technologies. *Chemosphere* **2017**, *168*, 599–605.
867 <https://doi.org/10.1016/j.chemosphere.2016.11.019>.
- 868 (47) Li, X.; Sun, D.; Chen, Y.; Wang, K.; He, Q.; Wang, G. Studying Compaction-
869 Decompaction of DNA Molecules Induced by Surfactants. *Biochem. Biophys.*
870 *Res. Commun.* **2018**, *495* (4), 2559–2565.
871 <https://doi.org/10.1016/j.bbrc.2017.12.151>.
- 872 (48) Mel'nikov, S. M.; Sergeyev, V. G.; Yoshikawa, K. Transition of Double-
873 Stranded DNA Chains between Random Coil and Compact Globule States
874 Induced by Cooperative Binding of Cationic Surfactant. *J. Am. Chem. Soc.*
875 **1995**, *117*, 2401–2408.
- 876 (49) Mel'nikov, S. M.; Yoshikawa, K. Discrete Coil-Globule Transition of Large DNA

- 877 Induced by Cationic Surfactant. *J. Am. Chem. Soc.* **1995**, *117*, 2401–2408.
- 878 (50) Mel'nikov, S. M.; Sergeyev, V. G.; Yoshikawa, K.; Takahashi, H.; Hatta, I.
879 Cooperativity or Phase Transition? Unfolding Transition of DNA Cationic
880 Surfactant Complex Cooperativity or Phase Transition? Unfolding Transition of
881 DNA Cationic Surfactant Complex. *J. Chem. Phys.* **1997**, *107* (17), 6917–6924.
882 <https://doi.org/10.1063/1.474932>.
- 883 (51) Sergeyev, V. G.; Mikhailenko, S. V.; Pyshkina, O. A.; Yaminsky, I. V.;
884 Yoshikawa, K. How Does Alcohol Dissolve the Complex of DNA with a Cationic
885 Surfactant? *J. Am. Chem. Soc.* **1999**, *121*, 1780–1785.
886 <https://doi.org/10.1021/ja981683+>.
- 887 (52) Clamme, J. P.; Bernacchi, S.; Vuilleumier, C.; Duportail, G.; Mély, Y. Gene
888 Transfer by Cationic Surfactants Is Essentially Limited by the Trapping of the
889 Surfactant/DNA Complexes onto the Cell Membrane: A Fluorescence
890 Investigation. *Biochim. Biophys. Acta - Biomembr.* **2000**, *1467*, 347–361.
891 [https://doi.org/10.1016/S0005-2736\(00\)00230-3](https://doi.org/10.1016/S0005-2736(00)00230-3).
- 892 (53) Dias, R.; Mel, S.; Miguel, M. G. DNA Phase Behavior in the Presence of
893 Oppositely Charged Surfactants. *Langmuir* **2000**, *16*, 9577–9583.
- 894 (54) Xu, L.; Feng, L.; Hao, J.; Dong, S. Compaction and Decompaction of DNA
895 Dominated by the Competition between Counterions and DNA Associating with
896 Cationic Aggregates. *Colloids Surfaces B Biointerfaces* **2015**, *134*, 105–112.
897 <https://doi.org/10.1016/j.colsurfb.2015.06.038>.
- 898 (55) Feng, L.; Xu, L.; Hao, J.; Dong, S. Controlled Compaction and Decompaction
899 of DNA by Zwitterionic Surfactants. *Colloids Surfaces A Physicochem. Eng.*
900 *Asp.* **2016**, *501*, 65–74. <https://doi.org/10.1016/j.colsurfa.2016.04.052>.
- 901 (56) Wang, L.; Wang, Y.; Hao, J.; Dong, S. Magnetic Fullerene-DNA / Hyaluronic

- 902 Acid Nanovehicles with Magnetism / Reduction Dual-Responsive Triggered
903 Release. *Biomacromolecules* **2017**, *18*, 1029–1038.
904 <https://doi.org/10.1021/acs.biomac.6b01939>.
- 905 (57) Wang, L.; Wang, Y.; Dong, S.; Deng, Y.; Hao, J. Nanocapsules of Magnetic Au
906 Self-Assembly for DNA Migration and Secondary Self-Assembly. *ACS Appl.*
907 *Mater. Interfaces* **2018**, *10*, 5348–5357.
908 <https://doi.org/10.1021/acsami.7b18689>.
- 909 (58) Wang, L.; Wang, Y.; Sun, X.; Zhang, G.; Dong, S. Versatile Self-Assembly and
910 Biosensing Applications of DNA and Carbon Quantum Dots Coordinated
911 Cerium Ions. *ChemPubSocEurope* **2017**, *23*, 10413–10422.
912 <https://doi.org/10.1002/chem.201701709>.
- 913 (59) Wang, L.; Wang, G.; Wang, Y.; Liu, H.; Dong, S.; Hao, J. Fluorescent Hybrid
914 Nanospheres Induced by Single-Stranded DNA and Magnetic Carbon
915 Quantum Dots. *New J. Chem.* **2019**, *43*, 4965–4974.
916 <https://doi.org/10.1039/c8nj06157b>.
- 917 (60) McLoughlin, D.; Langevin, D. Surface Complexation of DNA with a Cationic
918 Surfactant. *Colloids Surfaces A Physicochem. Eng. Asp.* **2004**, *250*, 79–87.
919 <https://doi.org/10.1016/j.colsurfa.2004.04.096>.
- 920 (61) Moradi, N.; Zakrevskyy, Y.; Javadi, A.; Aksenenko, E. V.; Fainerman, V. B.;
921 Lomadze, N.; Santer, S.; Miller, R. Surface Tension and Dilation Rheology of
922 DNA Solutions in Mixtures with Azobenzene-Containing Cationic Surfactant.
923 *Colloids Surfaces A Physicochem. Eng. Asp.* **2016**, *505*, 186–192.
924 <https://doi.org/10.1016/j.colsurfa.2016.04.021>.
- 925 (62) Lyadinskaya, V. V.; Lin, S. Y.; Michailov, A. V.; Povolotskiy, A. V.; Noskov, B.
926 A. Phase Transitions in DNA/Surfactant Adsorption Layers. *Langmuir* **2016**, *32*,

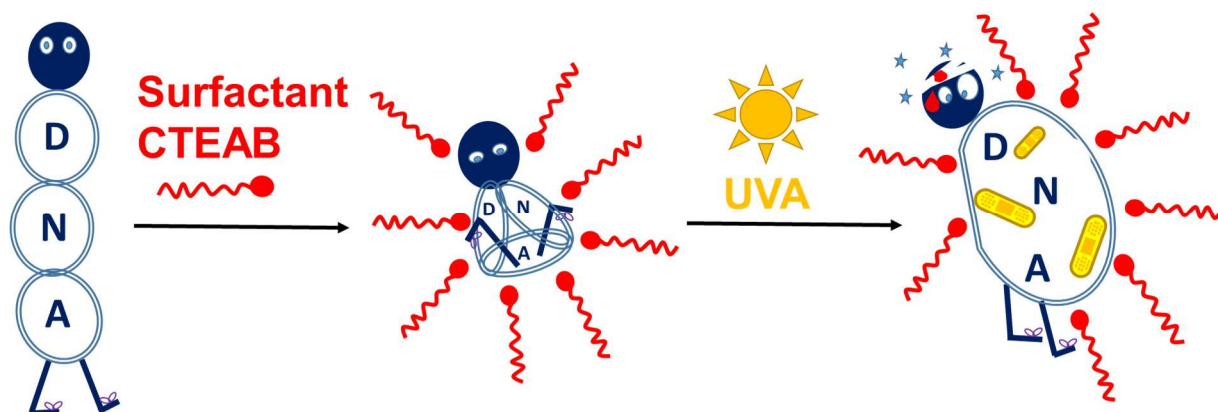
- 927 13435–13445. <https://doi.org/10.1021/acs.langmuir.6b03396>.
- 928 (63) Jumbri, K.; Rahman, M. B. A.; Abdulmalek, E.; Ahmad, H.; Micaelo, N. M. An
929 Insight into Structure and Stability of DNA in and Experimental Studies. *Phys.*
930 *Chem. Chem. Phys.* **2014**, *16*, 14036–14046.
931 <https://doi.org/10.1039/c4cp01159g>.
- 932 (64) Wang, H.; Wang, J.; Zhang, S. Binding Gibbs Energy of Ionic Liquids to Calf
933 Thymus DNA: A Fluorescence Spectroscopy Study. *Phys. Chem. Chem. Phys.*
934 **2011**, *13*, 3906–3910. <https://doi.org/10.1039/c0cp01815e>.
- 935 (65) Petrov, A. I.; Khalil, D. N.; Kazaryan, R. L.; Savintsev, I. V.; Sukhorukov, B. I.
936 Structural and Thermodynamic Features of Complexes Formed by DNA and
937 Synthetic Polynucleotides with Dodecylamine and Dodecyltrimethylammonium
938 Bromide. *Bioelectrochemistry* **2002**, *58*, 75–85. [https://doi.org/10.1016/S1567-](https://doi.org/10.1016/S1567-5394(02)00130-5)
939 [5394\(02\)00130-5](https://doi.org/10.1016/S1567-5394(02)00130-5).
- 940 (66) Zhang, L.; Dong, Y.; Zhang, X.; Guo, X. Micellization of Lactosylammonium
941 Surfactants with Different Counter Ions and Their Interaction with DNA. *J.*
942 *Chem. Eng. Data* **2016**, *61*, 2969–2978.
943 <https://doi.org/10.1021/acs.jced.5b01057>.
- 944 (67) Sutherland, J. C.; Griffin, K. P. Absorption Spectrum of DNA for Wavelengths
945 Greater than 300 Nm. *Radiat. Res.* **1981**, *86* (3), 399–410.
- 946 (68) Ikehata, H. Mechanistic Considerations on the Wavelength- Dependent
947 Variations of UVR Genotoxicity and Mutagenesis in Skin : The Discrimination of
948 UVA- Signature from UV-Signature Mutation. *Photochem. Photobiol. Sci.* **2018**.
949 <https://doi.org/10.1039/c7pp00360a>.
- 950 (69) Markovitsi, D. UV-Induced DNA Damage: The Role of Electronic Excited
951 States. *Photochem. Photobiol.* **2016**, *92*, 45–51.

- 952 <https://doi.org/10.1111/php.12533>.
- 953 (70) Merindol, R.; Loescher, S.; Samanta, A.; Walther, A. Pathway-Controlled
954 Formation of Mesostructured All-DNA Colloids and Superstructures. *Nat.*
955 *Nanotechnol.* **2018**, *13*, 730–738. <https://doi.org/10.1038/s41565-018-0168-1>.
- 956 (71) Cadet, J.; Douki, T. Formation of UV-Induced DNA Damage Contributing to
957 Skin Cancer Development. *Photochem Photobiol. Sci.* **2018**, *17*, 1816–1841.
958 <https://doi.org/10.1039/c7pp00395a>.
- 959 (72) Bancirova, M. Sodium Azide as a Specific Quencher of Singlet Oxygen during
960 Chemiluminescent Detection by Luminol and Cypridina Luciferin Analogues.
961 *Luminescence* **2011**, *26* (6), 685–688. <https://doi.org/10.1002/bio.1296>.
- 962 (73) Merkel, P. B.; Nilsson, R.; Kearns, D. R. Deuterium Effects on Singlet Oxygen
963 Lifetimes in Solutions. New Test of Singlet Oxygen Reactions. *J. Am. Chem.*
964 *Soc.* **1972**, *94* (3), 1030–1031. <https://doi.org/10.1021/ja00758a072>.
- 965 (74) Merkel, P. B.; Kearns, D. R. Radiationless Decay of Singlet Molecular Oxygen
966 in Solution. Experimental and Theoretical Study of Electronic-to-Vibrational
967 Energy Transfer. *J. Am. Chem. Soc.* **1972**, *94* (21), 7244–7253.
968 <https://doi.org/10.1021/ja00776a003>.
- 969 (75) Yagura, T.; Passaglia, A.; Carrião, C.; Garcia, M.; Ribeiro, C.; Rocha, R.;
970 Cestari, N.; Pedro, J.; Angeli, F.; Mendes, D.; et al. Free Radical Biology and
971 Medicine Direct Participation of DNA in the Formation of Singlet Oxygen and
972 Base Damage under UVA Irradiation. *Free Radic. Biol. Med.* **2017**, *108*, 86–93.
973 <https://doi.org/10.1016/j.freeradbiomed.2017.03.018>.
- 974 (76) Billen, D. The Role of Hydroxyl Radical Scavengers in Preventing DNA Strand
975 Breaks Induced by X Irradiation of Toluene-Treated Escherichia Coli. *Radiat.*
976 *Res.* **1984**, *97* (3), 626–629.

977 (77) Staehelin, J.; Hoigné, J. Decomposition of Ozone in Water in the Presence of
978 Organic Solutes Acting as Promoters and Inhibitors of Radical Chain
979 Reactions. *Environ. Sci. Technol.* **1985**, *19* (12), 1206–1213.
980 <https://doi.org/10.1021/es00142a012>.

981 Table of contents

982



983