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4 * Corresponding author: roberto.pisano@polito.it

5

6 **The Ice-Water Interface and Protein Stability: A Review**

7 Andrea Arsiccio, Roberto Pisano*

8

9 Department of Applied Science and Technology, Politecnico di Torino, 24 corso Duca degli Abruzzi, Torino,
10 10129 Italy

11

12 *E-mail of the corresponding author: roberto.pisano@polito.it

13 **ABSTRACT**

14 The ice-water interface is commonly encountered in our life, and comes into play in a wide number of natural
15 phenomena. Here, attention will be focused on its effects on protein stability, with specific reference to the
16 case of pharmaceutical proteins. This field represents a fascinating, and not yet fully understood, subject of
17 investigation. Some background information on the ice-water phase diagram, as well as to the mechanisms
18 of nucleation and crystal growth, will be provided. We will eventually discuss the effect of ice on protein
19 activity, reviewing the mechanisms of ice-induced denaturation that have been proposed so far and
20 discussing the strategies that may help prevent, or minimize, undesired loss of therapeutic activity.

21

22 **Keywords:** Crystallization, Proteins, Freeze-drying, Stabilization

23

24 **1. INTRODUCTION**

25 The ice surface is part of our everyday life and represents one of the most routinely encountered solid
26 interfaces. Despite being a very common and abundant material on Earth, ice shows unique and intriguing
27 properties that make it a fascinating subject of investigation. For this reason it plays a crucial role in a variety
28 of fields; it is central in glaciology and snow physics, but is also relevant in astrophysics and atmospheric
29 science, oceanography, cryo-biology and nucleation studies. Thanks to its availability, accessibility and
30 inherent safety (i.e., absence of toxicity, flammability, explosivity), it represents a superb model system for
31 phase transitions and deformation phenomena. The range of different scales involved in ice research, from
32 molecular phenomena to atmospheric events, is impressive, and clearly shows the transversality of this
33 topic.

34 It is therefore not surprising that the number of studies and publications in this area is already massive,
35 and growing fast. Several books have been written on the physics and chemistry of ice [1, 2, 3, 4, 5, 6]. More
36 than 3 million papers published to date deal with ice chemistry and physics, and an international symposium
37 (the International Conference on the Physics and Chemistry of Ice, PCI [7]) has been focusing on all aspects
38 of ice research for more than 55 years.

39 Considering the wide range of topics related to ice research discussed above, it would be impossible to
40 satisfactorily cover all of them. This review will therefore focus on the effect of the ice-water interface on
41 protein stability, a specific aspect that is more closely related with the authors' expertise.

42 Pharmaceutical proteins are becoming increasingly important in the treatment of a variety of human
43 diseases, and are commonly stored in the frozen or freeze dried state to reduce risks of degradation before

44 administration. Lyophilized formulations are generally preferred over frozen ones, because do not require to
45 maintain a controlled cold chain. About 30% of currently marketed biopharmaceuticals are introduced as
46 lyophilized products. Liquid formulations are also commonly used, and comprise about 50-60% of all biologic
47 dosage forms. Liquid formulations are preferred because of the low cost of manufacturing and ease of
48 administration, but cannot be used for very unstable molecules [8, 9].

49 Both freezing and freeze-drying involve the interaction of the protein with the ice-water surface, and this
50 may affect the final therapeutic potency, as will be discussed in the following. Understanding the
51 mechanisms and effects of protein-ice interaction would be essential for numerous applications, especially in
52 the pharmaceutical industry where this knowledge may help to minimize undesired loss of activity.

53 However, many questions remain open in this field, and a clear picture of the problem is not available yet.
54 We will show how experimental evidence suggests the central role of the ice surface on protein stability
55 during freezing, even though no definitive explanation is available about the underlying mechanisms.

56 We aim here to provide an as comprehensive as possible review on this subject, with the hope that it
57 could serve as a basis to further advance knowledge in this area.

58 In order to do this, some background information will first be provided. The crystal structure of ice will be
59 discussed, focusing in particular on hexagonal ice, which represents the most common form in everyday
60 application. The concept of the quasi-liquid layer (QLL, also called liquid-like layer), i.e., the thin film of liquid
61 water that is formed on the surface of ice crystals and which shows a peculiar behavior, will then be
62 introduced. Some hints to the mechanisms of growth and nucleation will also be provided, introducing the
63 experimental techniques that have been proposed in the literature to monitor these processes.

64 Finally, the effect of ice on protein stability will be addressed. Experimental evidence of ice-induced
65 destabilization will be presented, covering the extensive literature on this topic. Possible mechanisms at the
66 basis of these observations will be reviewed, also trying to clarify whether direct protein adsorption is
67 necessary or not. In this context, some space will be given to two very peculiar classes of molecules, i.e.,
68 antifreeze and ice nucleating proteins, whose unique behavior at the ice surface may help shed some light
69 on the freezing of biopharmaceuticals, as well. Finally, the relevant variables that influence ice-induced
70 denaturation of proteins, and may help to prevent or modulate it, will be described. Among them, the effect of
71 surfactants, cryoprotectants, protein concentration, cooling/thawing rate and nucleation temperature will be
72 covered.

73

74

75 2. CRYSTAL STRUCTURE OF ICE

76 2.1 Different Ice Polymorphs

77 Liquid water can freeze into several ice forms, depending on the temperature (T) and pressure (P) at which
78 crystallization is occurring. As a result, at least 17 crystalline ice phases have been experimentally observed
79 to date [10, 11, 12, 13, 14, 15]. The molecular structure of these phases is known, mostly thanks to neutron-
80 diffraction crystallographic studies. The large number of possible structures is mostly due to the open
81 tetrahedral arrangement of water, which can adapt to very different environments.

82 In these structures, each molecule is hydrogen-bonded to four neighboring water molecules. While in low-
83 pressure forms, such as the common hexagonal ice Ih, the O-O-O angles are close to the ideal value of
84 109.47°, these angles are distorted in higher pressure structures. For example, they range between 80° and
85 129° in ice II. When the pressure becomes very high, interpenetrating networks are eventually formed, as is
86 the case, for instance, of ice VII [12].

87 While the oxygen atoms show topological order (i.e., a tetrahedral coordination) in each phase, all the
88 polymorphs that can be directly crystallized from the liquid are hydrogen-disordered. These include the so-
89 called liquidus phases, namely ices Ih, III, V, VI, VII, and the two metastable phases IV and XII (see Figure
90 1).

91 When temperature is reduced, these disordered phases tend to order and transform into fully hydrogen-
92 ordered structures. However, hydrogen ordering needs molecular reorientations processes, which are
93 hindered at low temperature. Therefore, only ices III and VII undergo this transition spontaneously, ordering
94 into ices IX and VIII, respectively. By contrast, the formation of ices XI, XIII, XIV and XV needs to be
95 promoted by doping with bases or acids [16, 14, 17]. In this context, ice II is peculiar, because it is the only
96 hydrogen-ordered phase that shows no hydrogen-disordered counterpart [18]. At the same time, no
97 hydrogen-ordered analogue has been identified so far for ices XVI and XVII.

98 The different structures of ice mentioned so far are also shown in Figure 2. It is evident that the ice crystal
99 phases differ widely. For instance, the crystals structure may be hexagonal (ices Ih and XVII), cubic (ices VII,
100 X, XVI), rhombohedral (ices II and IV), tetragonal (ices III, VI, VIII, IX, XII), monoclinic (ices V, XIII), or
101 orthorhombic (ices XI, XIV, XV). Moreover, while ices Ih, XI, II, and XVII show open structures and relatively
102 low density, the ices VII, VIII and X network is extremely dense.

103 Amorphous structures of ice were also identified, including amorphous solid water (ASW) [20],
104 hyperquenched glassy water (HGW) [21], very high-density (VHDA) [22], high-density (HDA) [23] and low-
105 density (LDA) amorphous ice [24]. In the past years, neutron-diffraction techniques showed that the three

106 lower density forms, namely ASW, HGW and LDA, share a very similar structure, which resembles a
107 disordered, but tetrahedrally coordinated, fully hydrogen bonded network [25]. In contrast, the two denser
108 forms, HDA and VHDA, are structurally different.

109 The landscape of possible ice structures is therefore extremely complex. However, the picture seems not
110 complete yet, and many more ice polymorphs may be observed in the future. Several ice phases have been
111 predicted by molecular dynamics (MD) simulations or density functional theory (DFT) computations [26, 27,
112 28, 29, 30, 31, 32, 33, 34, 13]. For instance, 74963 potential ice structures have been recently identified by
113 DFT [35], even though it is not clear if these structures may be prepared experimentally.

114

115 **2.2 A Focus on Hexagonal Ice Ih**

116 As previously mentioned, structure Ih is the ordinary form of ice, which is most easily observed in common
117 experimental setup. Ice Ih displays a hexagonal lattice, relatively open and low-density. As a result, the large
118 hexagonal rings characteristics of ice Ih leave almost enough room for an interstitial water molecule. In the
119 ice Ih unit cell, the top and bottom faces are basal planes $\{0001\}$, while the six equivalent side faces are
120 called primary prism faces $\{10\bar{1}0\}$. Secondary prism faces $\{\bar{1}2\bar{1}0\}$ are also observed (see Figure 3).

121 Along with ice Ih, another metastable, hydrogen-disordered phase of ice exists at ambient pressure,
122 namely, ice Ic, which is characterized by a cubic crystal [36, 2, 3, 37, 38], and shows a lower nucleation
123 barrier compared to the Ih form [39]. Ice Ic is generally observed either in the Earth's atmosphere and in
124 extra-terrestrial environments [40], or in small-size droplets at very low temperature [41]. It was further shown
125 that ice Ic can be formed directly in the bulk water phase of a vitrified solution, for instance glucose at low
126 temperature [42]. More recently, it was also hypothesized that ice Ic may be an intermediate phase in the
127 pathway of heterogeneous ice nucleation [43]. However, it is not clear at present if fully cubic ice I (ice Ic)
128 can be prepared. In fact, it was observed from diffraction data that ice Ic samples were not entirely cubic, but
129 contained hexagonal stacking, as well [44]. This structure, where the hexagonal and the cubic stackings are
130 mixed, is called stacking-disordered ice I (ice I_{sd}), and is hydrogen-disordered. Interestingly, it was
131 suggested that I_{sd} may be even more stable than pure Ih ice [45]. No hydrogen-ordered counterpart has
132 been identified so far for ice I_{sd}.

133

134

135

136

137 **2.3 The Quasi-Liquid Layer (QLL)**

138 Ice interfaces may be disordered even below the equilibrium melting temperature, resulting in the so-called
139 surface premelting [46, 3, 47, 12]. A quasi-liquid layer (QLL), that represents an intermediate state between
140 the solid and bulk liquid, is therefore formed.

141 The extension of the QLL increases rapidly as temperature approaches the equilibrium melting value [46,
142 48, 49, 50], because thermal fluctuations of the intermolecular distance become larger in these conditions.
143 The actual thickness of the QLL as a function of temperature is not well known, but, as a rough estimate, it
144 should be comparable to the lattice spacing at $T \approx -10$ °C, and should rapidly increase approaching the
145 melting temperature [46].

146

147 **3. ICE NUCLEATION AND GROWTH**

148 **3.1 Fundamentals of Nucleation**

149 During the freezing process, water needs to nucleate first, and the ice nuclei which are formed in this stage
150 subsequently grow to form crystals. In this context, nucleation plays a central role [51].

151 According to the classic nucleation theory (CNT) [52], the free energy change ΔG (see Figure 4)
152 associated with the formation of a nucleus in a supercooled solution is the sum of a negative bulk
153 contribution ($-V\Delta g_v$, where V is the volume of the nucleus), and a positive surface term ($A\gamma$, where A is the
154 surface of the nucleus, and γ the interfacial tension),

155

$$\Delta G = -V\Delta g_v + A\gamma \quad (1)$$

156

157 For pure water, the ice/liquid interfacial tension is generally assumed to be on the order of 0.033 J/m²
158 near the triple point, dropping to approximately 0.020 J/m² at -40°C [53].

159 Foreign bodies, e.g. the walls of the container, impurities or other particles present in the solution, can
160 lower the interfacial free energy and reduce the energy barrier for nucleation. In this case, heterogeneous
161 nucleation ensues, and a correlation factor f may be used to quantify the decrease in the energy barrier [54,
162 55, 56],

163

$$f = \Delta G_{heter}^* / \Delta G_{homo}^* \quad (2)$$

164 where ΔG_{heter}^* is the heterogeneous nucleation barrier (see Figure 4).

165 The factor f depends on the chemical compatibility between the nucleus and the substrate, which can be
166 described in terms of the contact angle θ . Moreover, it also depends on the radius of curvature r_s of the
167 substrate. Defining two new variables $m = (\gamma_{sf} - \gamma_{sc})/\gamma_{cf} \approx \cos \theta$ and $r' = r_s/r_{cr}$, it is therefore possible to
168 write $f = f(m, r')$. In the previous equation for m , γ_{sf} , γ_{sc} and γ_{cf} are the interfacial free tension values
169 between the substrate and the fluid, the substrate and the crystal or the crystal and the fluid, respectively.

170 While Ih ice is thermodynamically stable below 0 °C, homogeneous nucleation does not occur
171 spontaneously until very low temperatures. It has been suggested that the onset of homogeneous nucleation
172 may be -40 °C [57, 58, 59].

173 However, computational simulations predicted that no ice crystals would spontaneously form above -71
174 °C [60], and also experimental results suggest that homogeneous nucleation scarcely occurs even far below
175 -40 °C [61]. The possibility to reach this high degree of supercooling is due to the high energy barrier for
176 homogeneous nucleation.

177 Because of this, ice crystallization is generally controlled by heterogeneous nucleation events. In this
178 case, the presence of foreign particles lowers the energy barrier by decreasing the interfacial free energy.

179

180 **3.2 Understanding the Growth of Ice Crystals**

181 Ice crystals growth is governed by two physical phenomena, namely, surface attachment kinetics and the
182 diffusion processes within the solution [47].

183 A key variable in this context is the degree of supercooling, which is often defined as $\Delta T_{surf} = T_{eq} - T_{surf}$, where
184 T_{eq} is the equilibrium freezing temperature, and T_{surf} the temperature at the ice-water surface during growth.

185 The growth rate v_g can then be written as,

186

$$v_g \approx K_g \Delta T_{surf} \quad (3)$$

187

188 where K_g is a kinetic coefficient. Ice crystal growth is influenced by the different growth rates on each facet,
189 which in turn depends on their different step energies.

190 The step energy is defined as the energy required to create the edge of a one-molecule-high terrace on a
191 faceted surface. For instance, the ice/water step energy on the basal face near the triple point is about $5.6 \times$
192 10^{-13} J/m [62, 63] while is essentially zero for the prism faces. Experimental data suggest that the most
193 stable ice-water interface at 0 °C is the secondary prismatic face (see Figure 3), followed by the primary

194 prismatic plane and, as a distant third, by the basal facet. This results in the typical hexagonal shape of ice Ih
195 [64].

196 However, the morphology of the ice formed is extremely variable. For instance, it was reported to vary
197 from circular disks when $T_{surf} < 1$ °C, to dendritic plates when $T_{surf} < 2$ °C, unbranched needle-like structures
198 if $T_{surf} \approx 4$ °C, branched needle-like structures if $T_{surf} \approx 8$ °C and platelets if 10 °C $< T_{surf} < 30$ °C [65]. Either
199 the surface attachment kinetics, or the mass and heat transfer through the system may be the controlling
200 mechanism, thus determining the final expression of the kinetic coefficient.

201 Figure 5 shows an example of a typical temperature profile during freezing of a pharmaceutical solution.
202 The nucleation and growth phases have been highlighted. The liquid solution is first supercooled to a value
203 below the equilibrium freezing point (segment A-*). Supercooling represents a metastable state, during which
204 water molecules tend to form clusters with long-living hydrogen bonds [66]. However, these clusters are still
205 unstable, and break up quickly, as discussed in section 3.1. When the temperature is low enough to allow
206 crossing of the energy barrier for the nucleation process, ice crystallization occurs rapidly in the whole
207 product (point * in Figure 5). In all pharmaceutical solutions heterogeneous nucleation is observed, and the
208 degree of supercooling often lies in the range of 10-15 °C or more [67]. A sharp increase in product
209 temperature to a value close to the equilibrium freezing point is observed at the onset of nucleation. The ice
210 crystals growth (segment B-C) then proceeds through the addition of molecules to the interface. Here, the
211 latent heat of crystallization is almost compensated for by the heat removed through the already frozen
212 product, and the temperature remains nearly constant. Finally, to ensure complete solidification, the frozen
213 product is typically cooled down to -40 / -50 °C (segment C-D).

214

215 **4. MONITORING, PREDICTING AND CONTROLLING THE ICE CRYSTAL SIZE**

216 **4.1 Monitoring the Freezing Process**

217 Larger ice crystals are generally preferred for protein-based pharmaceuticals [68], as will be discussed in
218 detail in section 5, because this results in a smaller ice/freeze-concentrate surface area, and therefore
219 reduced risk of adsorption.

220 The extension of the ice/freeze-concentrate surface is, therefore, a fundamental parameter for protein
221 activity preservation during freezing, and should be strictly controlled. However, at present, this task cannot
222 be easily achieved.

223 Generally, the parameters that mostly influence the ice/freeze-concentrate surface area are the cooling
224 rate used during freezing, and the nucleation temperature. A high nucleation temperature, and/or a low

225 cooling rate, result in larger crystals, and hence smaller surface area [69, 70]. In this context, it should be
226 considered that, in many fields, the range of cooling rates that can be explored is limited by equipment
227 capabilities. For instance, common freeze dryers cannot achieve very fast cooling rates (e.g., $> 1 \div 2 \text{ K min}^{-1}$),
228 and are therefore limited to slow cooling protocols.

229 The temperature profile during freezing of a pharmaceutical solution, which gives information about both
230 nucleation temperature and cooling rate, may be monitored using several tools. For instance, thermocouples
231 or resistance thermal detectors (RTDs) may be used. Thermocouples are typical in lab-scale equipment,
232 while RTDs are common in production-scale ones because are more robust and can be sterilized [71, 72].
233 Another option for temperature monitoring are the optical fiber sensors [73], where the sensing element
234 shows a temperature-dependent refractive index. Alternatively, if wire connections should be avoided,
235 passive transponders may be used, like the temperature remote interrogation system (TEMPRIS).

236 However, the presence of a sensor within the sample undergoing freezing could affect its ice nucleation
237 behavior, therefore modifying the ice crystal size and ice-water surface area. For this reason, plasma
238 sputtering was proposed to embed thermocouples within the containers walls, so as to avoid interaction with
239 the product [74, 75]. Optical fiber sensors may be also used noninvasively, for instance fusing the fiber in the
240 container bottom or embedding it in the controlled-temperature shelf where freezing is occurring [73].

241 Recently, the use of an infrared thermocamera was proposed to noninvasively monitor the freezing
242 process [76], and was successfully combined with mathematical modelling to predict the final ice crystal size
243 [77]. However, this method directly measures the temperature of the vial glass, and a model needs to be
244 used to extract the actual product temperature [76]. Through vial impedance spectroscopy (TVIS) [78, 79] is
245 another promising approach for the noninvasive monitoring of freezing, which exploits the variations in the
246 bulk electrical properties during phase transformations.

247 These techniques make it possible to monitor the temperature profile, and some of them also the position
248 of the freezing front and therefore the duration of the process. However, coupling with a modelling approach
249 is needed to obtain information on the ice/freeze-concentrate surface area extension, as will be
250 described in section 4.2.

251 During freezing, liquid water is separated as ice crystals, and the solutes that may be present in the
252 system cryo-concentrate, forming a viscous matrix. If the ice crystals are then removed by sublimation, as it
253 is done in the context of freeze drying, a porous structure is eventually formed in the freeze-concentrated
254 matrix. The few techniques that are currently available to directly measure the extension of the ice/freeze-
255 concentrate interface rely on the fact that the ice crystal size after freezing coincides with the pore size after

256 lyophilization, provided that neither collapse nor shrinkage is observed during drying. Therefore, the specific
257 surface area of the dried cake provides a measure of the extension of the ice-water interface, and could be
258 obtained by BET [80]. Scanning electron microscopy of lyophilized products (see Figure 6) may also be used
259 to obtain information on the average pore size D_p , which could then be linked to the ice-water surface area
260 S_{iw} , for instance assuming that the crystals (and therefore also the pores) have cylindrical shapes,
261

$$S_{iw} = \frac{4m}{D_p \rho} \quad (4)$$

262 where m is the mass of crystallizable water, and ρ the ice density. Image analysis could help in the
263 automation of SEM image analysis, as well [81, 82].

264 Microscopy observation of frozen products was also suggested [83], and another promising experimental
265 technique is the X-ray micro-computed tomography, which allows the reconstruction of the entire porous
266 internal structure of lyophilized samples [84].

267 Monitoring the freezing process, and its impact on product morphology, is therefore possible. In the next
268 section, we will briefly describe how these measurements may be integrated, or used to validate, modelling
269 approaches for the prediction of the ice/freeze-concentrate surface area.

270

271 **4.2 Modelling Approaches to Predict the Ice/Freeze-Concentrate Surface Area**

272

273 The prediction of ice crystal size generally requires knowledge of the temperature profiles within the solution
274 being frozen. These could be measured, as described in the previous section, or extracted from simulations
275 [85, 86], and may then be combined with empirical [87, 88, 89], or mechanistic [90, 77] models for crystal
276 sizing. A simulation approach, that takes into account the variation in temperature during freezing, as well as
277 cryoconcentration effects and the ice/freeze-concentrate interface formation, has been recently proposed to
278 predict the risk of both cold- and ice-induced denaturation of proteins [91].

279 Numerical methods have also been developed to reproduce growth morphologies of ice crystals, for
280 instance phase-field models [92, 93, 94], that should apply well to the growth of ice from liquid water [47].

281 Our understanding of the effect of the ice surface on protein stability may also substantially benefit from a
282 deeper knowledge of the molecular-scale phenomena involved. For this purpose, molecular dynamics
283 simulations represent a promising tool, which has been extensively used to simulate the ice-water interface

284 [95, 96, 97, 98, 99, 100, 101, 102, 103], and may provide some interesting information about protein/ice
285 interaction, as will be discussed in detail in section 5.

286 The ability to predict the extension of the ice/freeze-concentrate surface is not enough if we cannot then
287 control it, at least to some extent. This will therefore be the subject of the next section.

288

289 **4.3 Controlling the Ice/Freeze-Concentrate Surface Area**

290 If we consider that the ice/freeze-concentrate interface is a major source of protein instability during freezing,
291 it is clear that the possibility to control its extension would be extremely beneficial. In principle, adsorption
292 and denaturation phenomena may be minimized by promoting the formation of a small surface area. This
293 could be achieved reducing the cooling rate, and inducing nucleation at a high temperature. However, while
294 the cooling rate can be easily adjusted, the nucleation temperature is generally a stochastic variable, and its
295 value is randomly distributed [104]. This results in huge heterogeneity, and limited possibility to control
296 product morphology. This heterogeneity is hardly compatible with the stringent requirements of the
297 pharmaceutical industry, and several techniques have been developed over the years to address this
298 problem [67, 105, 106, 107].

299 An approach that may be used to increase the ice crystal size is annealing, which consists in holding the
300 frozen product at a temperature above the glass transition for a given amount of time. During annealing,
301 large ice crystals grow at the expense of smaller ones [108].

302 A number of techniques have also been developed, that allow control of the nucleation temperature. For
303 instance, electrofreezing [109, 110] uses a high voltage pulse to trigger nucleation in supercooled water.
304 However, individual electrodes need to be inserted in each sample, and in direct contact with the product,
305 which is not compatible with GMP (Good Manufacturing Practice) conditions.

306 In the case of the ice-fog technique [111, 112, 113, 114, 115] nucleation is triggered by the introduction of
307 small ice particles into the vials. These particles act as foreign bodies and promote heterogeneous
308 nucleation, as discussed in section 3.1.

309 Another possible solution is ultrasound-induced ice nucleation [116, 117, 118, 119, 120, 121], where
310 ultrasounds are used to start the nucleation process in a noninvasive way. However, it is not yet clear
311 whether this technique may be applied to sensitive proteins, as the localized high temperatures generated by
312 cavitation, and the bubble themselves, may potentially favor aggregation or other denaturation routes.

313 Two methods have also been developed, that are based on variations in pressure within the chamber. In
314 the high-pressure-shift or depressurization method [122, 123, 124], the pressure is first increased to 1.5-4.5

315 bar, and then rapidly brought back to the atmospheric value. In the second approach, known as vacuum
316 induced surface freezing, or vacuum induced nucleation [125, 126, 127, 128, 129, 130], pressure is reduced
317 to induce nucleation by promoting evaporation from the surface of the product, and then quickly released to
318 avoid undesired boiling or blow-up of the formulation.

319 Large ice crystals are obtained when using these controlled nucleation techniques, and a possible impact
320 of that on protein stability will be addressed in section 5.4.

321

322 **5. ICE AND PROTEIN STABILITY**

323 **5.1 Evidence of Ice Effect on Protein Stability**

324 It is well known that the freezing process may have detrimental effects for a protein, leading to denaturation,
325 aggregation and loss of biological activity. Numerous phenomena could contribute to the undesired
326 conformational changes of the protein, including cold denaturation, cryo-concentration, or the formation
327 of ice crystals [131, 132].

328 The physical environment of the protein is strongly affected by the cryo-concentration process, which
329 induces variations in ionic strength and relative composition of solutes. pH shifts due to crystallization of
330 buffer components [133], or phase separation phenomena [134, 135] may occur. On the one hand, if the
331 protein being processed is stable in a narrow range of pHs, the precipitation of buffer components may lead
332 to undesired denaturation. Actually, it was even shown that freeze-drying may result in remarkable changes
333 in apparent acidity even without buffer crystallization. These changes in the apparent acidity may be related
334 to changes in pK_a upon water removal, or preferential inclusion of a basic component by ice crystals, and
335 were observed to correlate with the degradation rates of acid-sensitive compounds [136]. On the other hand,
336 the generation of a new interface during phase separation, as well as the possible partitioning of the protein
337 into a phase with low concentration of stabilizers, may have detrimental consequences. The rate of some
338 degradative reactions, such as hydrolysis and oxidation, may even increase during the freezing process

339 [137, 138, 139]. Recently it was proposed that the formation of water clusters at subzero temperature
340 catalyzes proton transfer reactions, that are involved in many chemical degradation pathways like hydrolysis
341 and deamidation [140].

342 At low temperature the hydration of nonpolar residues also becomes less unfavorable, and this leads to
343 the possibility for water molecules to penetrate the protein structure, promoting the exposure of its
344 hydrophobic core and the partial loss of secondary structure. This phenomenon is referred to as cold
345 unfolding, and is driven by the reduced enthalpic barrier against water-hydrophobes interaction that occurs

346 when lowering the temperature. The result is the formation of compact, partially unfolded states of the
347 protein, characterized by a high degree of solvent penetration [141, 142, 143, 144, 145, 146, 147]. A
348 possible way to study the effects of supercooled water on protein stability is the confinement in nanoporous
349 matrices, that inhibits crystallization. Exploiting this technique, it has been shown that the structural
350 transitions of proteins are dictated by the thermodynamic and kinetic modifications of their hydration water
351 [148, 149].

352 However, the formation of ice crystals was shown to represent the most critical destabilizing factor. A
353 dramatic decrease in the average phosphorescence lifetime of the Trp-48 residue was detected in solutions
354 of the azurin protein upon ice formation [150]. This suggested that protein destabilization occurred as soon
355 as ice crystals were formed.

356 The denaturation of several proteins during freeze-thawing, including ciliary neurotropic factor (CNTF),
357 phosphofructokinase (PFK), LDH, glutamate dehydrogenase (GDH), interleukin-1 receptor antagonist (IL-
358 1ra) and tumor necrosis factor binding protein (TNFbp), was found to be mostly related to the increase in the
359 area of the ice-water surface [151].

360 Lower recovery of catalase, β -galactosidase and LDH activity was observed during fast freezing [152],
361 and the formation of insoluble human growth hormone (hGH) aggregates was also found to increase with
362 increasing cooling rates [153]. This occurs because more rapid cooling leads to smaller ice crystals, which
363 have a greater surface area to volume ratio than larger crystals.

364 Sarciaux et al. [154] proposed a mechanism of aggregate formation involving denaturation of bovine
365 immunoglobulin (IgG) at the ice/freeze-concentrate interface. This denaturation was reversible upon freeze-
366 thawing, but became irreversible after freeze-drying and reconstitution. Also in this case, quick cooling
367 resulted in increased aggregation. Increasing the protein concentration improved the percentage of
368 recovered protein [152, 154]. This occurs because the extension of the ice/freeze-concentrate interface is
369 finite, and the number of protein molecules adsorbed at the surface cannot exceed a given value. When this
370 value is reached, increasing the bulk concentration reduces the percentage of adsorbed

371 molecules [154].

372 Exploiting the change in Trp fluorescence between the native and denatured state, it was observed that
373 the stability of the azurin mutant C112S from *Pseudomonas aeruginosa* was remarkably perturbed in ice
374 [155]. Moreover, the extent of destabilization depended mainly on the size of the liquid water pool in
375 equilibrium with ice. At the same time, it was observed that protein-ice interactions increased the solvent
376 accessible surface area of the native fold, and/or decreased that of the denatured conformation [155].

377 In line with this observation, a remarkable loss of activity was observed in frozen lactate dehydrogenase
378 (LDH) matrices. However, concentrated solutions at the same temperature and composition, but without ice,
379 resulted in no degradation, suggesting that ice formation is the controlling factor for protein
380 denaturation [68].

381 Similarly, an infrared spectroscopy investigation of LDH and human immune globulin (IgG) revealed an
382 increase in intermolecular β -sheet structures close to the ice crystals, which is indicative of aggregation
383 [156]. In contrast, the infrared spectra for these two protein molecules collected distant from the surface of
384 ice crystals were very similar to spectra collected from the initial solution. This suggests that the vicinity of
385 the ice surface is key to promote conformational changes. In a similar study, the aggregation of IgG2 at -10
386 °C was related to the formation of the ice/freeze-concentrate interface [157].

387 Molecular dynamics simulations of hGH also suggested a change in protein conformation at the ice
388 surface, with a significant increase in the non-polar surface area exposed, while no notable conformational
389 change was detected in unfrozen solutions at the same temperature [158]. Partial unfolding of the GB1
390 hairpin was similarly observed in metadynamics simulations at the ice-water interface [159].

391 Overall, these results suggest that prevention of ice-induced denaturation represents a key issue
392 whenever a protein is subjected to a freezing process. In the next section, we will review the mechanisms
393 that have been proposed so far in the literature to explain this phenomenon.

394

395 **5.2 How Does the Ice Interface Affect Protein Stability?**

396 In the previous section, evidence about the negative impact of ice formation on protein stability was
397 presented. However, a question that spontaneously arises from the previous discussion is: what are the
398 reasons at the basis of the ice-induced denaturation of proteins? What makes it difficult to answer is the
399 absence of chemical differences between water and ice. Moreover, the structural differences are also
400 minimal, as both water and ice are composed of a tetrahedral network of hydrogen bonds. Why two
401 substances that are so similar would affect protein behavior in such a different way? This represents an
402 intriguing and complex field of investigation, also because not many experimental techniques are currently
403 available to fully address this problem.

404 Strambini and Gabellieri [150] suggested that the conformational changes of proteins may arise from the
405 direct interaction between the protein and the ice surface, as schematized in Figure 7a. In this context,
406 accumulation of milk proteins [160] and albumin [161, 162] near the ice surface was detected, using either
407 light and transmission electron microscopy or confocal Raman microspectroscopy. Recombinant human

408 interferon- γ (rhIFN- γ) was found to accumulate at the ice/liquid interface during lyophilization, but with
409 significantly smaller intensity than at the air/liquid surface [163]. Also, accumulation of rhIFN- γ to the
410 ice/liquid surface alone was found to be not responsible for aggregation, and a subsequent drying step was
411 necessary to induce particle formation [164].

412 However, unless the protein has an antifreeze behavior (see section 5.3), there is no real evidence of
413 direct protein adsorption onto the ice crystals. By contrast, solid-state NMR studies seem to indicate that the
414 hydration shell of non-antifreeze proteins does not freeze below the freezing temperature of the bulk solution
415 [165, 166]. For instance, ubiquitin keeps its entire hydration shell even at -35 °C, and this prevents direct
416 interaction with the ice surface [167]. It is generally believed that most proteins should behave like ubiquitin,
417 and that their hydration shell should remain in the liquid form until a temperature which is much lower than
418 the equilibrium freezing value [168]. No direct interaction with ice would hence be possible above this
419 temperature.

420 High-resolution synchrotron X-ray diffraction results further suggest that bovine serum albumin tends to
421 partition into the quasi-liquid layer above ice crystals (see section 2.3), but without being directly adsorbed
422 onto the ice surface [169]. A similar behavior was observed for two other proteins, namely recombinant
423 human albumin and a monoclonal antibody, in a more recent investigation [170].

424 A different behavior is generally observed only in presence of antifreeze proteins (AFPs) [170, 171, 172],
425 whose peculiar behavior will be briefly addressed in section 5.3. Therefore, another explanation for the ice-
426 induced denaturation of proteins, which is not related to direct adsorption at the ice-water surface, should
427 exist.

428 In this context, it should be remembered that the physical microenvironment of a protein confined within
429 the QLL may be substantially different compared to the bulk. More specifically, the stabilizer may remain in
430 the bulk, and may not be able to exert anymore its cryoprotective effect. In this context, Bhatnagar et al.
431 [170] proposed a picture of the protein/ice interaction where the concentration gradients in the liquid phase
432 adjacent to the ice crystals depend on the mobility of the species. Larger species tend to concentrate closer
433 to the ice surface, because of their lower mobility. At the same time, the pH in the QLL may decrease
434 because of the negative charge on the surface of ice crystals [170, 173]. The electrical double layer which is
435 eventually formed may result in an increased concentration of cations, including protons (see Figure 7b).

436 Another possible explanation involves the entrapment of air at the ice surface. Using fluorescence
437 microscopy [156], it was observed that several air bubbles may remain trapped between ice crystals. Air
438 bubbles have also been observed by optical microscopy [174] and small angle neutron scattering [175].

439 Therefore, proteins may denature at this hydrophobic air-water interface, as outlined in Figure 7c. A
440 similar mechanism was also proposed in a recent work [132], where it was pointed out that the growth of ice
441 crystals leads to an increase in the concentration of dissolved air gasses. The cryo-concentration of oxygen
442 may accelerate oxidation reactions during freezing [176, 177]. It was also estimated that the extension of the
443 air bubbles interface may be significantly larger than the already existing interface on the top of the container
444 [132].

445 Recently, a disordered population of ice crystals was detected by high-resolution synchrotron X-ray
446 diffraction in frozen solutions of recombinant human albumin, lysozyme, an insect AFP and a monoclonal
447 antibody [170]. This disordered population of ice crystals was identified as a high pressure form of ice,
448 tentatively Ice III or Ice IX (see section 2.1). This observation was explained by the volume expansion that
449 may occur during ice formation, and which may result in mechanical stresses and high local pressure.
450 Values of freeze-induced pressure exceeding 2 kBar have been theoretically estimated [132]. Pressure-
451 induced unfolding of the protein may hence occur [178], and the combination of elevated pressure and low
452 temperature may have a synergetic effect on protein unfolding [179] (see Figure 7d).

453 Finally, in a recent molecular dynamics investigation of protein L [180], the effect of the ice surface was
454 explained as an enhancement of cold denaturation phenomena. The protein was found to be destabilized in
455 presence of an ice slab, compared to the bulk solution at the same temperature but without ice. No direct
456 interaction between the protein and the surface was evidenced, but the observed denaturing effect seemed
457 to be mediated by the nearby layer of liquid (or, better, liquid-like) water molecules. These molecules were
458 significantly slowed down by the presence of ice, and could form a significantly larger number of hydrogen
459 bonds with the protein, especially with the nonpolar patches that are generally poorly hydrated. These
460 hydrogen bonds were also remarkably strong, and promoted the solvent-penetration of protein L and
461 consequent exposure of its hydrophobic core, which is a common feature of cold denaturation [147] (see
462 Figure 7e).

463 In the next sections, we will first present two very peculiar classes of molecules, namely, antifreeze and
464 ice-nucleating proteins, whose unique behavior may help us understand the phenomenology of ice-peptide
465 interaction. Afterwards, possible approaches to counteract ice-induced denaturation of proteins will be
466 discussed.

467
468
469

470 **5.3 The Peculiarity of Antifreeze (AFPs) and Ice-Nucleating (INPs) Proteins**

471 In this section, attention will be devoted to two specific classes of proteins, namely, antifreeze (AFPs) and
472 ice-nucleating (INPs) proteins. These molecules have peculiar characteristics, and our general
473 understanding of protein-ice interaction may substantially benefit from a deeper analysis of their behavior.

474 AFPs have the ability to bind to nascent ice nuclei, therefore inhibiting their growth [181, 182]. For
475 instance, it was reported that AFPs can inhibit the growth of both basal and prism planes of ice I_h [183].
476 They represent the natural way many organisms protect themselves against freezing damage, by
477 depressing, in a noncolligative way, the freezing point of water. In a broader perspective, AFPs represent a
478 central element in the problem of ice recognition by biomolecules. What makes their role and action even
479 more puzzling is the remarkable difference of AFP structure between different classes of organism. This
480 indicates that the depression of the freezing point can be exerted by extremely different structural motifs.

481 A spontaneous question about AFPs is what mechanisms drive their interaction with ice. Since the ice
482 surface is characterized by the presence of OH groups, it was first proposed that the hydrophilic groups on
483 the ice-binding sites (IBS) of AFPs may hydrogen-bond with ice [182, 184]. However, many AFPs do not
484 expose H-bonding groups at their IBS. On the contrary, it was observed that hydrophobic residues are
485 largely present on the IBS [185]. It was therefore suggested that hydrophobic groups were crucial [186, 187],
486 together with a flat-binding surface [188]. However, neither H-bonding nor hydrophobic groups can be the
487 only explanation. H-bonding groups would provide affinity, but no specificity, as they tend to interact more
488 with liquid than ice water [189]. At the same time, hydrophobic groups would make it possible to achieve
489 specificity, but are not compatible enough with the hydrophilic ice surface. This implicates that both groups
490 should be involved [190].

491 Exploiting a simulation approach, it was suggested that the arrangement of water molecules in proximity
492 of the IBS may play a role in the action of AFPs [191, 192, 193]. In fact, both a slight increase in tetrahedral
493 order [194] and slower relaxation dynamics were observed in the hydration water of AFPs [195, 196]. These
494 water molecules seem to adopt a highly ordered structure, forming a clathrate-like structure, similar to ice,
495 around the ice-binding site of AFPs [190, 189]. This structure surrounds the hydrophobic groups of the IBS,
496 while being anchored at the edges by H-bonds to the polar groups. Therefore, the AFPs may bind to ice
497 thank to this ice-like structure that is formed at their IBS. These ordered layer of water molecules may be
498 released upon binding, leading to a net entropic gain [197, 198]. NMR suggests that only the portion of AFPs
499 hydration shell at the IBS is in direct contact with the ice surface. The remaining part of the hydration shell
500 does not undergo freezing, behaving similarly to the hydration shell of non-AFPs proteins [167].

501 A further question that may arise is whether this ice-like structure is always present, or, on the contrary,
502 forms only close to the ice surface. Molecular simulations of TmAFP (a hyperactive insect AFP, which shows
503 the best lattice matching with ice Ih, see Figure 8a) indicate that the second option is correct [199],
504 suggesting that a preordering of hydration water is not necessary for ice recognition. The formation of the
505 clathrate-like structure at the IBS is therefore probably induced by the close presence of an ice layer. This
506 suggests that ice has an effect on the surrounding liquid water layers [172].

507 Another class of interesting molecules is represented by ice-nucleating proteins (INPs), that are used by
508 several bacteria, such as *Pseudomonas syringae*, to trigger ice formation at temperatures close to the
509 equilibrium value [200].

510 INPs are structurally and chemically similar to AFPs, but are considerably bigger and can result in the
511 formation of molecular clusters. The larger surfaces that are eventually formed are capable of nucleating ice.
512 A common example of INP is InaZ, produced by *Pseudomonas syringae*, which is approximately 1200
513 residues-long [201]. Its structure includes degenerate octapeptide repeats, a subpopulation of which includes
514 the sequence GSTXT(A/S), where X is an unconserved amino acid. Recently, *ab initio* structures of the
515 GSTSTA segment were resolved by electron microdiffraction [202]. It was discovered that both homochiral
516 and racemic GSTSTA (see Figure 8b-c) form amyloid-like protofibrils, that display antiparallel β -sheets.

517 Molecular dynamics simulations suggested that INPs may be anchored to the cell surface in such a way
518 to expose ice-active sites to the surrounding water [204, 205]. It was proposed that threonine and serine
519 amino acids, that are largely represented on these sites, should mimic the basal plane of ice. This is possible
520 because of their OH groups and the presence of clathrate water molecules that effectively induce nucleation
521 [190, 206].

522 Later on, sum frequency generation (SFG) spectroscopy was used to study the INP of *Pseudomonas*
523 *syringae*, namely, the protein inaZ [207]. This study demonstrated that hydrogen bonding at the water-
524 bacteria contact promotes structural ordering on the adjacent water network. The unique hydrophilic-
525 hydrophobic motifs at the ice-nucleating site, together with the effective removal of latent heat due to
526 nucleation, are highly effective in triggering the formation of stable ice crystals. Later on, it was also
527 suggested that only large surfaces, like INPs clusters, may effectively order hydration water into ice-like
528 structures [199].

529 *Pseudomonas syringae* may also be added to a solution being cooled down to trigger nucleation. This
530 was done to promote the formation of nuclei at higher temperature [69, 208, 209, 210]. However, this

531 approach cannot provide a real control of the nucleation temperature, and cannot therefore substitute the
532 techniques discussed in section 4.3.

533

534 **5.4 How to Counteract Ice-Induced Denaturation of Proteins**

535 From the previous discussion, it is evident that the ice-induced denaturation of proteins should be adequately
536 controlled to maximize the recovery of therapeutic activity after freezing. In this context, two main classes of
537 strategies could be adopted; the first relies on the selection of suitable operating conditions, while the second
538 involves optimization of the formulation.

539 From the point of view of the operating conditions, the two variables that mostly affect protein stability
540 during freezing are cooling rate and nucleation temperature. As previously mentioned, a low cooling rate and
541 a high nucleation temperature are associated with the formation of larger ice crystals, and therefore smaller
542 ice/freeze-concentrate surface area. This, in turn, should minimize ice-induced denaturation of proteins. In
543 line with these considerations, a correlation has often been observed between cooling rate and protein
544 stability, with higher recovery at lower cooling rates [151, 152, 153]. However, this is not true for all proteins.
545 In the case of particularly unstable molecules, such as myoglobin at low pH, a fast freezing protocol was
546 found to maximize protein stability [91]. In this case, the formation of a cryoconcentrated matrix at high
547 viscosity, where cold unfolding of the protein is kinetically inhibited, should be promoted as quickly as
548 possible.

549 While the cooling rate can easily be controlled and adjusted, the nucleation temperature is a stochastic
550 variable. However, as discussed in section 4.3, several strategies have been developed to address this
551 problem. The impact of controlled nucleation techniques on protein stability has also been investigated in
552 recent works. For instance, the controlled nucleation strategy based on the depressurization method was
553 found to improve LDH stability after freeze-thawing [211]. The depressurization method applied to a highly
554 concentrated monoclonal antibody also suppressed glass fogging, which is the undesired migration of
555 protein solutions up on the inner walls of glass vials [212]. Another controlled nucleation technique, namely,
556 the ice-fog method, was applied to monoclonal antibody formulations [213], and resulted in reduced particle
557 formation in highly concentrated systems. However, the addition of polysorbates was more effective in
558 decreasing particle level. Also, the authors observed no difference in particle formation between the
559 controlled and spontaneously nucleated samples at low concentration [213]. The benefits of vacuum induced
560 surface freezing (VISF) on the stability of the human growth hormone (hGH) were also investigated [214].

561 In this case, both HPLC-SEC and a cell-based potency assay indicated that there was no dramatic
562 difference in the behaviour of hGH at low concentration when either VISF or spontaneous nucleation were
563 used. In the case of very unstable molecules, such as myoglobin at low pH, the application of VISF proved to
564 be detrimental. In this case, the benefits of a smaller ice/freeze-concentrate interface are offset by the
565 necessity to introduce two holding steps at low temperature and low product viscosity during application of
566 the VISF. During these equilibration stages, cold denaturation of myoglobin may quickly occur [91].

567 Finally, annealing is another technique that may affect protein stability. While it does not make it possible
568 to control the nucleation temperature, it nevertheless promotes the formation of larger ice crystals. The
569 resulting decrease in specific surface area of the ice/freeze-concentrate interface may improve protein
570 stability. This was the case, for instance, of bovine IgG as model protein [154]. It should also be considered
571 that the thawing process may also be dangerous for protein activity.

572 In this context, the thawing rate is a crucial parameter, as slow thawing promotes the recrystallization
573 process, with small ice crystals growing into larger ones. While the growth of larger ice crystals during
574 freezing, for instance by annealing, was found to be beneficial, recrystallization has been observed to be
575 detrimental during thawing, as it promoted undesired interfacial or shear stress for proteins at the ice-water
576 interface [215]. Moreover, during the process of ice melting, the amorphous cryo-concentrated phase will still
577 not have the same composition as the initial fully-liquid solution. Problems due to unequal distribution of
578 solutes may therefore occur during thawing, as well. For this reason, it is generally advisable to perform a
579 fast thawing [132].

580 For what concerns the choice of the formulation, different possibilities exist to improve protein recovery
581 after freezing. Typical biopharmaceutical formulations include cryo/lyo-protectants (e.g., sugars, polyols,
582 amino acids, polymers), buffering species, to control the pH, and in many cases also surfactants, to
583 counteract surface-induced denaturation, and bulking agents (e.g., mannitol, glycine), to improve cake
584 resistance. A comprehensive description of the type/amount of excipients found in commercial products is
585 out of the scope of this review. We will therefore focus on those case studies where formulation components
586 have been shown to affect protein stability at the ice surface, starting from surfactants. For instance, it was
587 observed that the addition of small amounts of Tween 80 or Tween 20 protected proteins from ice-induced
588 denaturation [151, 163, 216]. Addition of the same surfactant to LDH and a human IgG formulation resulted
589 in a decrease in intermolecular β -sheet structure formation at the ice surface, which is indicative of
590 diminished aggregation [156]. Surfactants are amphiphilic molecules that tend to locate at interfaces, thereby
591 sterically preventing protein adsorption [217, 218]. This may explain why they have often been reported to

592 prevent ice-induced denaturation of proteins. However, as discussed in section 5.2, there is increasing
593 evidence that non-AFP proteins do not bind to the ice interface, but rather remain confined in the QLL above
594 the surface. The steric repulsion exerted by surfactants that coat the ice interface may, therefore, be not
595 enough to account for the observed stabilizing effect. Molecular dynamics simulations of the GB1 peptide
596 suggest that surfactants tend to surround the protein at the ice surface, with their hydrophilic heads oriented
597 towards the peptide [159]. On the one hand, this orientation prevents denaturation, because the exposure of
598 the protein hydrophobic core is unfavorable in these conditions. On the other hand, the formation of a
599 protein-surfactant complex hinders aggregation, as well. The stabilizing role of surfactants may hence be
600 explained according to an orientation-dependent mechanism.

601 Apart from surfactants, cryoprotectants may be added, including sugars (for instance sucrose, trehalose,
602 glucose, lactose), polyols (e.g., sorbitol and glycerol), polymers (albumin, dextran, polyvinylpyrrolidone and
603 hydroxyethyl cellulose are common examples), and amino acids (such as glycine, proline, arginine etc.). For
604 instance, Strambini and Gabellieri [150] observed that the addition of glycerol and sucrose reduced the
605 protein conformational changes induced by ice-formation during freezing. They suggested that the stabilizing
606 action of these excipients may be considered as a combined effect of decreasing the freezing temperature
607 and reducing the adsorption affinity of the protein by coating the surface of ice. However, sterical exclusion
608 from the ice interface can hardly be the only mechanism to explain the role of cryoprotectants. Actually, the
609 opposite was often observed, with excipients being expelled in the bulk freeze-concentrated solution and
610 promoting a closer approach between the protein and the ice surface [170, 162].

611 The crystallite size and microstrain for Ih crystals was also evaluated for different protein formulations
612 [170]. A higher microstrain, compared to pure water, was observed in all protein-containing samples,
613 indicating that proteins may promote the formation of defects during ice crystal growth. In contrast, the
614 microstrain level was consistently lower in all non-protein samples (containing, for instance, sucrose or
615 histidine), suggesting that the effect of excipients on the ice structure should be minimal. At the same time,
616 SEM analysis of freeze-dried cakes shows that the choice of the formulation strongly affects the pore size,
617 and, therefore, the extension of the ice/freeze-concentrate interface. It has been hypothesized that this may
618 be related to a different energetic cost for forming the ice/freeze-concentrate interface (i.e., different
619 interfacial tension) in presence of different cosolutes [90].

620 It was also suggested [150] that the cosolutes may exert their protective action by being preferentially
621 excluded from the protein surface. This should make the unfolding process thermodynamically unfavorable
622 [219]. In particular, molecular dynamics simulations suggested that exclusion from specific patches on the

623 protein surface should be crucial for protein stability at the ice surface [158, 180]. However, the mechanism
624 of preferential exclusion should be prevailing only at the beginning of the freezing process, when
625 cryoconcentration is not yet complete. During the last stages of freezing, the matrix that separates from ice is
626 so concentrated that other mechanisms come into play [220, 221]. At high excipient concentration, the
627 vitrification theory [222, 223], the water replacement scenario [224, 225] and the water entrapment
628 hypothesis [226, 227, 228] apply. Vitrification invokes the formation of a viscous, glassy matrix [229] where
629 protein movements are hindered, while water entrapment envisions the formation of a cage of excipient
630 molecules around the protein, where water is entrapped and slowed down. While these two are kinetic
631 mechanisms, the water replacement theory suggests that a thermodynamic stabilization applies, where the
632 excipient substitutes water in satisfying the hydrogen-bonding requirements of the protein. All these
633 mechanisms of stabilization are effective only if the stabilizer remains in the same amorphous phase where
634 the protein is. Therefore, crystallization of the cryoprotectant may reduce protein stabilization, also because it
635 results in another surface onto which the protein may adsorb and denature [216].

636 Another typical component of a protein formulation is the buffer, which should maintain the pH in a range
637 of values where the active ingredient is stable. In this context, it should be remembered that some buffer
638 species may undergo selective crystallization, and this could result in undesired pH shifts. This is the case,
639 for instance, of sodium and potassium phosphate [230, 231].

640 Finally, as previously mentioned, a high protein concentration is beneficial to minimize the effect of the
641 ice-water interface [152, 154]. On the one hand, the percentage of protein molecules that are in the region
642 perturbed by the presence of ice decreases when the concentration is increased. On the other hand, volume
643 exclusion effects may arise at higher concentration. For instance, the cold denaturation temperature of β -
644 lactoglobulin was found to decrease significantly when increasing the protein concentration [232].

645

646 **6. CONCLUSIONS**

647 In this work, an overview of the chemical and physical properties of the ice-water interface, and of its effects
648 on protein stability, was provided. Rather than giving answers, the objective of this work was to raise
649 questions that, according to the authors opinion, are worth further investigation.

650 More specifically, the following points should be addressed:

- 651 i. Is the Ih form of ice the only crystal structure that is relevant for pharmaceutical applications? As
652 evidenced using high-resolution synchrotron X-ray diffraction [170], other structures of the ice

653 phase diagram described in section 2.1 may be important, and this aspect should be further
654 investigated.

655 ii. Do the advantages of controlled nucleation approaches make them worth application in the
656 manufacturing of pharmaceuticals and biopharmaceuticals? At present, the controlled nucleation
657 techniques discussed in section 4.3 are not applied by pharmaceutical industries in the
658 production of commercially available drugs. Further investigations should be added to evaluate
659 their effect on protein stability, and the first steps in this direction have been discussed in section
660 5.4 .

661 iii. What are the mechanisms at the basis of ice-induced denaturation of proteins? Some hypotheses
662 in this context have been described in section 5.2, and should further by addressed. The answer
663 to this question may benefit from a deeper understanding of the peculiarity of antifreeze and ice-
664 nucleating proteins, as discussed in section 8.

665 iv. What are the conditions that minimize the denaturing effect of ice on protein stability? Some
666 possible strategies to prevent, or minimize, ice-induced denaturation of proteins have been
667 described in section 5.4. However, a more robust approach to the selection of appropriate
668 conditions for the freezing of protein-based therapeutics would be desirable. It is evident that
669 many variables come into play, and it is therefore probably impossible to give a unique answer,
670 valid for all classes of proteins. In this regard, the application of mathematical models, such as
671 those mentioned in section 4.2, may help to reduce the number of experiments to be performed,
672 providing at the same time a better understanding of the underlying phenomena. The modelling
673 approaches should be multiscale, covering both the molecular mechanisms of protein
674 conformational changes and the effect of process variables on the critical attributes of the
675 product.

676

677 The hope of the authors is that this work may help to focus the attention of both industries and academies in
678 this direction, indicating possible objectives and providing a basis for future investigations.

679

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1188 **LIST OF FIGURES**

1189

1190 Figure 1: Phase diagram of ice, where the hydrogen-disordered forms are shown in orange, the ordered
1191 ones in green and the polymeric ice X in blue. The stable phases are written in red and bold, while
1192 metastable ones are displayed in smaller size. An exclamation point is used to indicate transitions that are
1193 not yet known. Reproduced from reference [10], with modifications.

1194

1195 Figure 2: Structures of the various polymorphs of ice (generated using the GenIce algorithm [19]). The
1196 tetrahedral arrangement of hydrogen bonds in ice is also shown in the right panel on the last row of the
1197 figure. In all crystal structures, this same motif is repeated, where each molecule accepts two hydrogen
1198 bonds, and donates two to its neighbors.

1199

1200 Figure 3: Hexagonal ice Ih, where the main crystal faces (basal, primary prismatic and secondary prismatic)
1201 are shown.

1202

1203 Figure 4: Free energy variation upon homogeneous (black) and heterogeneous (red) nucleation at different
1204 nuclei size r . These free energy changes are the sum of a negative bulk (dotted) and a positive surface
1205 (dashed) contributions, and reach a maximum at $r = r_{cr}$.

1206

1207 Figure 5: Evolution of temperature during freezing of an aqueous solution.

1208

1209 Figure 6: Sample SEM images of freeze-dried products. Unpublished data from the authors.

1210

1211 Figure 7: Possible mechanisms of ice-induced denaturation of proteins. (a) Adsorption at the ice interface
1212 [150] (b) Partitioning of the protein in the QLL, where the concentration of stabilizer is decreased, and the
1213 local pH is more acid than in the freeze-concentrated solution (FCS) [170] (c) Accumulation of air bubbles at
1214 the ice surface [156, 132] (d) Pressure-induced unfolding due to mechanical stresses associated with the ice
1215 growth [170] (e) Enhancement of cold denaturation phenomena, mediated by the liquid molecules in the QLL
1216 [180].

1217

1218

1219 Figure 8: (a) Cartoon representation of TmAFP (PDB structure 1EZG [203]), where β -sheets are in yellow,
1220 turns in cyan and coils in white. The N-terminus and C-terminus are highlighted in red and blue respectively.
1221 (b-c) L-GSTSTA (PDB code 6M9I [202]) (b) and racemic-GSTSTA (PDB code 6M9J [202]) (c) from inaZ (INP
1222 protein from *Pseudomonas syringae*). Glycine amino acids are shown in white, serine in yellow, threonine in
1223 red and alanine in blue.