Impact of Phosphorylation on alpha-Synuclein Structural Determinants

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Abstract: Serine 129 and, to a lesser extent, serine 87 can appear phosphorylated in the intrinsically disordered protein human α-synuclein (AS), a key player in Parkinson's disease, where it accumulates in proteinaceous aggregates. Intriguingly, both phosphorylations are located in a highly negative potential region of the protein. Here we used molecular simulation to provide insight in the selective phosphorylation by polo-like kinase 2 (PLK2), in both monomeric and fibrillar forms of AS. We suggest that phosphorylation does not impact on the structural determinants of the physiological AS conformational ensemble, as the phosphate group is mostly solvated. Our findings are consistent with experimental data on the non-acetylated, non-physiological form of the protein. The phosphate groups of pAS may be solvated also in the aggregated form.

1. Introduction. Parkinson's disease (PD) is the second most common neurodegenerative disease after Alzheimer's disease,[1] affecting several million people worldwide.[2,3] The typical pathological hallmark is the accumulation of fibrillar protein inclusions, know as Lewy bodies (LBs) and Lewy neurites (LNs) in the brain.[4,5] The major component of LBs and LNs are fibrillar forms of the human α-synuclein (AS) protein.[3,6] AS is a 140 amino acid 'disordered' conformational ensemble both in aqueous solution and in vivo.[7,1] In physiological conditions, the protein is acetylated on the first residue, although in vitro studies suggest this N-terminal acetylation does not significantly change the fibrillization propensity in vitro. In LBs, a significant fraction of AS is phosphorylated on serine 129.

However, it is still unclear whether this post-translational modification (PTM) plays a pathological and/or physiological role.[9–11] The formation of the Ser129-O-PO_3^{2-} group at the C-terminus (residues 96-140) is intriguing, because the latter is highly negatively charged (pAS) (Figure 1)[2]. The negatively charged C-term differs from the other two regions of the protein: the positively charged N-terminus (residues 1-60) and the overall neutral non-amyloid component (NAC) region (residues 61-95) (Figure 1). Its impact on the structural determinants is not known.[3]

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MDVFMKGLSKAKEGVVAAAEKTKQGVAEAAGKTKE  35
GVLYVGSKTKEGVVHGVATVAEKTKEQVTNVGGAV  70
VTGVTAVAQKTVEGAGSIAAATGFVKKDQLGKNEE 105
GAPQEGILEDMPVDPDNEAYEMPSEEGYQDYEPEA 140
```

Figure 1. Sequence of amino acids in α-synuclein; positively charged residues are highlighted in blue and negatively charged ones in red.

Here, we used computational tools in an effort at addressing these important issues. First, we used electrostatic modeling to provide a rationale for the phosphorylation at the C-term by target kinases.[15] Next, we investigated the impact of the PTM on the protein in its monomeric form and in the fibrils. Our investigation on monomeric AS here builds upon our AMBER-based Replica Exchange with Solute Tempering 2 (REST2)[16] enhanced sampling predictions of wild-type[17,18] and mutants[18] of the conformational ensemble of AS monomer in aqueous solution, in its physiological form[19] [4]. The calculations are based on the two force fields tailored for IDPs. These are the DES-Amber ff99SB[43]

[1] It acquires instead some degree of structure when bound to the membrane or to cellular partners.[8]

[2] Phosphorylation introduces as many as two negative charges in AS at physiological pH (the pKa_1 and pKa_2 of phosphoserine are <2 and 5.6[12]). However, it might be possible that in that negative potential the phosphate is monoprotonated (Ser129-O-PO_2OH^-, pASH). The effect of protonation is discussed in the Supplementary Information)

[3] The CD spectra of the *non-N-term acetylated*, non physiological form of the protein[13,14] in solution points to significant changes in the structural ensemble. However, the structure of the physiological form differs from that of the non-aceylated one, so conclusions cannot be made from these studies

[4] To the best of our knowledge, these are the only molecular simulation studies so far on AS' physiological form in explicit solvent.[5]

and the AMBER a99SB-*disp* force fields.[20] The latter has already been successfully used for the unacetylated form of the protein in the free form[20 44] and in the presence of ligands.[21] The conformational space of the protein was efficiently explored using the REST2 algorithm and it was shown to reproduce a variety of biophysical properties of the protein. However, the simulations presented here face the challenging doubly charged phosphate group. While the force field for phosphorylation (phosphorylated serine, threonine, and tyrosine) are present in the most widely used force fields, from AMBER[45] (DOI: 10.1007/s00894-005-0028-4) , to CHARMM[46,47] and to GROMOS[48] , and also even quite recently (https://doi.org/10.1021/acschemneuro.2c00611), some of these parametrizations (including that of AMBER) have at times shown artifacts.[49,50] Here, our caculations are based on (i) the standard a99SB-*disp* Amber forcefield[45] (DOI: 10.1007/s00894-005-0028-4) for the protein and the solvent, but with a specific, AMBER-compatibe parametrization of the phosphate group[51] and (ii) the DES-Amber force field, for which phosphate parameters have been calibrated based on osmotic coefficient calculations.[52]

2. Methods

Electrostatic modeling. The X-ray structures of the AS kinases PLK2, CK1, CK2, GRK5 and LRRK2 were taken from the Protein Data Bank[53] (IDs 4I5P,[54] 3UYS,[55] 1NA7,[56] 4TNB[57] and 6VNO[58] respectively). The binding site and active site location were identified using ProRule .[59,60] The sequence alignments in the area of the predicted binding site were performed using Clustal Omega.[61] Figure 2 in the SI shows that a common motif across all these enzymes can be found.

For monomeric AS, we considered the main representative conformer from a cluster analysis of the molecular simulations performed here (see below), present for 1.44 % of the simulation time. For the fibrils, we took the solid state structure (PDBid 2N0A).[62]

The surface potentials of the proteins along pAS and AS (in solution and in the aggregate forms) were calculated using the Poisson-Boltzmann equation using APBS and PDB2PQR[63] and visualized in PyMOL.[64]

Molecular simulations. The initial structure of the monomer best reproduced the chemical shifts for the first twelve residues in ref.[17] The phosphate group was added to Ser129 by editing the structure in PyMOL.[65]

The proteins were inserted in a water-filled dodecahedral simulation box with periodic boundary conditions and minimum distance of 3.5 nm between the protein and the box edges. Na^+ and Cl^- ions were added to neutralize the system and achieve a concentration of 150 mmol L^{-1}. Table 1 shows the composition of the systems, how many atoms and which type of them.

Table 1. Number of atoms in the simulation box for the three systems simulated here. The TIP4P-D water model uses a forth dummy atom to simulate water, thus the total number of atoms including dummy atoms is given in brackets.

	Protein	Water	Sodium	Chlorine
AS	2,020	190,533 (254,044)	186	176
pAS	2,023	172,359 (229,812)	171	159

The simulations were based on: (i) the a99SB-*disp* force field[20] together with a modified version of the TIP4P-D water model compatible with the force field; (ii) the DES-Amber force field[43] and the standard TIP4P-D water (See Table 20 in the SI for a full list of the parameters used). The proteins turned out not to be in contact with their images at distances 1.2 nm or lower during these simulations. Long range electrostatics were evaluated using the Particle-Mesh Ewald (PME) method,[66] using a cutoff distance of 1.2 nm in real space. Also the Van-der-Waals interactions featured the same cutoff.

Constant temperature conditions were achieved by coupling the systems with the Nose-Hoover thermostat[67] at 300 K and a time constant of 0.5 ps. Constant pressure was achieved with a Parrinello-Rahman barostats[68] at 1 bar and a time constant of 2 ps (Table 20). The LINCS algorithm was used for all bonds involving hydrogen atoms.[69] The equations of motions were integrated using the `md` leap-frog algorithm, with a timestep of 2 fs.

The proteins underwent an energy minimisation (Table 15 in the SI for details). The systems were then heated in the NVT ensemble from 0 K to 300 K in 1 ns (Table 17 in the SI). Finally, 100 ns REST2 simulations in the NVT ensemble were carried. We checked that the proteins are not in contact with their images at distances lower than 1.2 nm during any of these simulations.

A cluster analysis was carried out with the `gmx cluster` code in GROMACS.[70,71] A cutoff of 0.5 nm and the `linkage` method were chosen.

The following properties were calculated: (i) The radius of gyration R_g, calculated using the `gmx gyrate` module from GROMACS. (ii) The hydrodynamic radius, calculated from the radii of gyration using a linear fit proposed by Allison et al.[32] (iii) The NMR chemical shifts of the C_α atoms, calculated using `shiftx2`.[72] (iv) The secondary structure elements, calculated using the MDTraj[73] and DSSP[74] codes. (v) The CD spectra, using DichroCalc.[75] Only conformations after 12 ns were considered. Additionally the average of all used clusters weighted to their occurrence was calculated. (vi) The solvent accessible surface area (SASA) using the `gmx sasa` code from GROMACS. (vii) The contact map of the protein using the `gmx mdmat` code in GROMACS. (viii) Radial distribution functions (RDF) from the oxygen atoms of serine 129 using `trrdf` and `int_trrdf` using the SPEADI[76] code developed by the authors. (viii) Hydrogen bonds were defined by a distance between oxygen or nitrogen atoms with polar hydrogen below 0.3 nm, and an angle with the hydrogen-polar atoms between 160 and 180 degrees. To identify the hydrogen bonds VMD was used.[77] (ix) Salt bridges were defined by a distance between to charged atoms in the protein at a distance below 0.32 nm. The `pairdist` module from GROMACS was used.

3. Results and Discussion

Electrostatic modeling. Polo like kinase 2 (PLK2)[78,79] is thought to be the most important kinase phosphorylating AS on S129.[80] Previous work[81] and electrostatic modeling performed here shows that the cleft between the active and binding sites is positively charged (Figure 2). This is expected to steer the interaction with the negatively charged C-terminus (including S129), both in its monomeric, intrinsically disordered form (Figure 2(b)) and in the fibrils (Figure 2(c)), where the NAC region forms a stacked structure and the N-term and C-term.[6] PLK2 also phosphorylates S87, albeit at a lower extent.[82] Phosphorylation does not seem to occur at S42 and S9.[82] Notably, while S87 is still located in a negative potential region of the protein (albeit less negative than S129) in solution (Figure 2(b)) and in fibrillar

[6] An analysis of other kinases phosphorylating S129 is presented in the SI

forms (Figure 2(c)), the other two serine residues are located at the N-term, characterized by a more positive potential. Thus, we may expect an 'electrostatic steering' also for S87 but not for the other two, consistently with experimental evidence.

Molecular simulations of the monomer. We performed REST2 simulations[16] for 100 ns, using 32 replicas afor both AS and pAS monomers. Additionally 100 ns of MD were carried out. We performed simulations using both the the DES-Amber and the a99SB-*disp* force fields (for the latter we also investigated the protein with a monoprotonated phosphate (pASH). We report here the results for the first calculations, while the second can be found in the SI.

Convergence. We inspected: (i) the running averages of the percentage of residues featuring any secondary structure and in a helix structure (Figures 7 to 9 in the SI)), plotted as a function of the simulation time, reached a plateau after 12 ns of the simulation (see SI); (ii) the running averages of the chemical shifts of C_α (same Figures) which converge closely to the experimetnal values (Figure 10 in the SI) and (iii) the RMSD (Figure 13 in the SI). The use of the latter however has limitation as AS is an IDP.[83] . Based on this analysis, we calculated structural properties in the interval 12-100 ns.

Comparison with experimental data. The computational setup turns out to reproduce the available experimental data (NMR, CD and hydrodynamic radius)[84–86] available for AS (See SI).

Effect of phosphorylation. In Figure 3 the structures of the ten most representative structures of AS and pAS are offered. They were determined with clustering. Those ten structures make up 35 % and 33.7 % of the simulation time respectively for AS and pAS.

The calculated hydrodynamic radius R_H (Table 2) and the radius of gyration R_g decrease upon phosphorylation. However the SASA increases in the NAC region (Table 3).[7] The intramolecular interactions between the NAC region and the other regions slightly increase, as shown by the contact map (Figure 6). Accordingly, the intermolecular hydrogen bonds increase, within the caveat that it features a large standard deviation (Table 2). Consistently, the distribution of the number of such interactions show a wide normal distribution (Figure 17 in the SI).

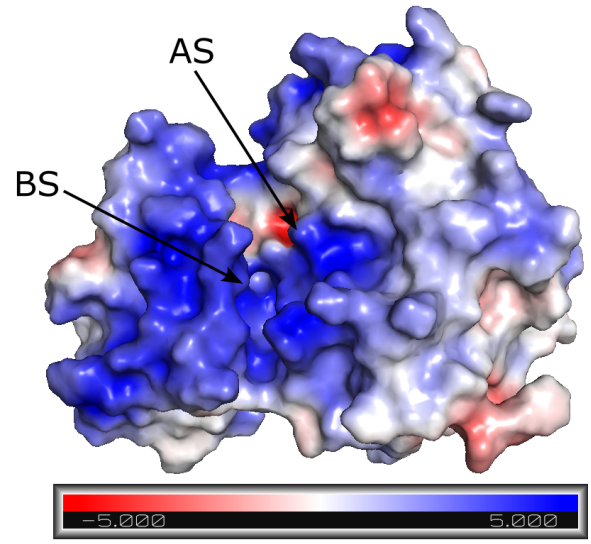
These H-bonds are almost exclusively formed within every single domain (see Fig. 4).

The number of salt bridges increases upon phosphorylation. The most persistent salt bridges common to both forms involve the N-term and NAC regions (K23-E20 and K58-E61, respectively, see Figure 4). Please notice that given the disordered nature of IDPs intramolecular contacts are labile. Different salt bridges can form over longer time scales or at different starting points. Few salt bridges are formed between the C-terminus and one of the two other domains.

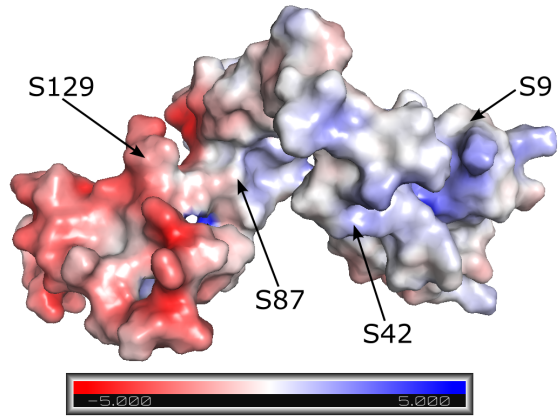
We conclude that the compactness of the AS conformational ensemble slightly increases upon phosphorylation, but maybe not in the NAC region. This is associated with a small increase of intramolecular interactions. This is what one may expect given an increase of negative charge at the C-terminus which can increase its interaction with the rest of the protein, and, particularly, with the positively charged

[7] The C-terminus – N-terminus distances experience large fluctuations, making this analysis not conclusive (Figure 14 in the SI).

(a) PLK2



(b) Monomer



(c) Fibril

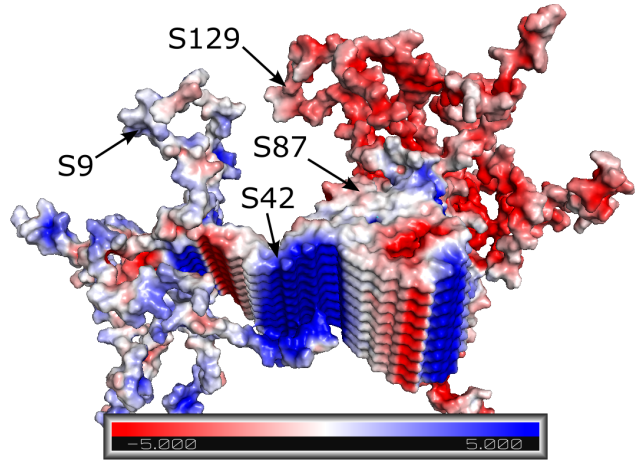


Figure 2. (a) PLK2[54] with indications for the binding site (BS) and active site (AS). Electrostatic potential of (b) the monomer and (c) fibrils[62] as calculated by the Poisson-Boltzmann equation with (b) all serine positions highlighted; or (c) the serine positions of the first protein in the fibril highlighted.

Table 2. Calculated properties of AS and pAS. (i) Gyration (R_g) and hydrodynamic R_H radii of the entire proteins and of the NAC regions. The experimental value of R_H is 28.7 Å.[85] (ii) Average number of hydrogen bonds. (iii) Average number of salt bridges. Standard deviations are indicated in parenthesis.

	R_g [Å]	R_H [Å]	R_g(NAC) [Å]	R_H(NAC) [Å]	N_{HB}	N_{SB}
AS	35.6 (±12.8)	35.1 (±6.1)	23.8 (±16.4)	28.3(±11.3)	19.52 (±4.28)	1.54 (±1.23)
pAS	28.0 (±9.6)	31.0 (±5.8)	17.2(±9.2)	23.1 (±8.1)	20.67 (±4.32)	1.86 (±1.75)

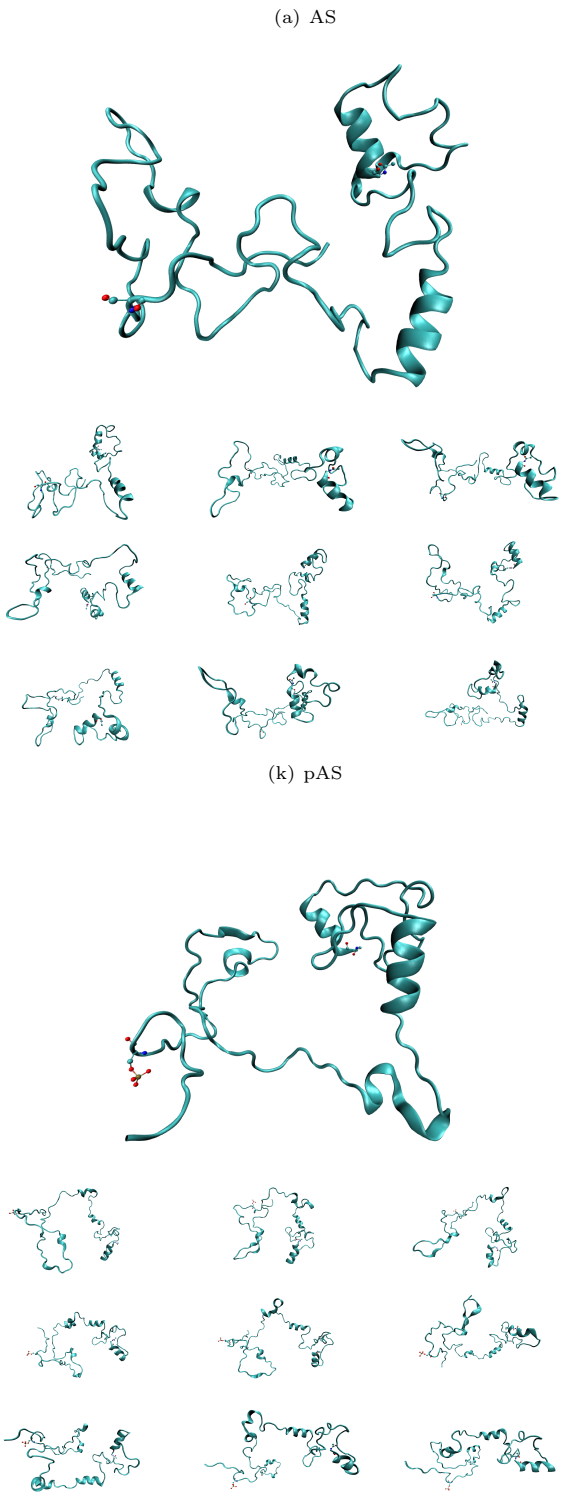


Figure 3. Representative structures of AS (a) and pAS (k) as determined by clustering. The acetyl group at the N-terminus and the residue at position S129 are shown as ball and sticks. The percentage of occurrence of the structures decreases from left to right and top to bottom (see Table 1 in the SI).

Table 3. Average solvent accessible surface areas (SASA) in AS and pAS in the NAC-Region and N- and C-terminus.

	SASA_N [nm^2]	SASA_{NAC} [nm^2]	SASA_C [nm^2]
AS	0.96 (±0.41)	0.87 (±0.31)	1.11 (±0.32)
pAS	0.90 (±0.42)	0.91 (±0.32)	1.13 (±0.39)

N-terminus. The phosphate group interacts to a small extent with sodium ions (Figure 21 in the SI) and, even less, with the protein residues (Figure 20 in the SI). In fact, the phosphate group is fully solvent exposed, as shown by a plot of the phosphate oxygen-water oxygen radial distribution functions (RDFs) (Figure 5). This might be caused, at least in part, by the absence of surrounding basic residues. However, one has to take into account also that current force field may lead to a overestimation of the number of interacting water molecules (See SI) This effect is even larger with the standard a99SB-*disp* force field (See SI). Within these caveats, we suggest that the electrostatic field of the phosphate is strongly reduced by its solvation and largely does not impact the C-terminus-N-terminus interactions. This lack of interaction may also in part be explained by AS containing no arginine residues that are known to interact strongly with phosphate groups,[87] yet none of the lysine residues present in the N-terminal domain formed salt bridges with S129 during the simulation (see Figure 3(a)).

The scenario of S129 in AS is dramatically different: the side chain does interact with the solvent at much lower rate. The Oγ atom has only 2 water hydrogen (Figure 5) and no sodium ions in its surrounding. The serine oxydril group forms instead a variety of *intramolecular* H-bonds (with K80, K96, K97 , K102, E126, E130 and E131 (Figure 20 in the SI).[8]

The serine in AS is instead involved in intermolecular contacts and, indeed AS features a larger number of the latter relative to pAS. In addition, The electrostatic interactions with the rest of the protein may be screened by the presence of positively charged counterions.

Analysis of the fibrils. The PTM introduces additional negative charges far from basic residues as observed in the monomeric form: K6 is the closest basic residue, located at 2.39 nm from S129. This residue is expected to fully solvated, in contrast to the NAC region.[62] At the speculative level, we may expect that water and counterions (absent in the structure[62]) may stabilize the phosphate group similarly to what observed for the monomer.

4. Conclusions. Here, we investigated the effects of phosphorylation on the structural ensemble of AS in solution in fibrillar forms. The residue is selected to be phosphorylated by its cognate kinase enzyme in a negatively charge region such as the C-term (both in solution and in the fibrils), because of its high positive potential. Once phosphorylated, the AS monomer does not undergo very large con-

[8] S129 backbone units interact with the solvent and nearby protein hydrogens in both AS and pAS.

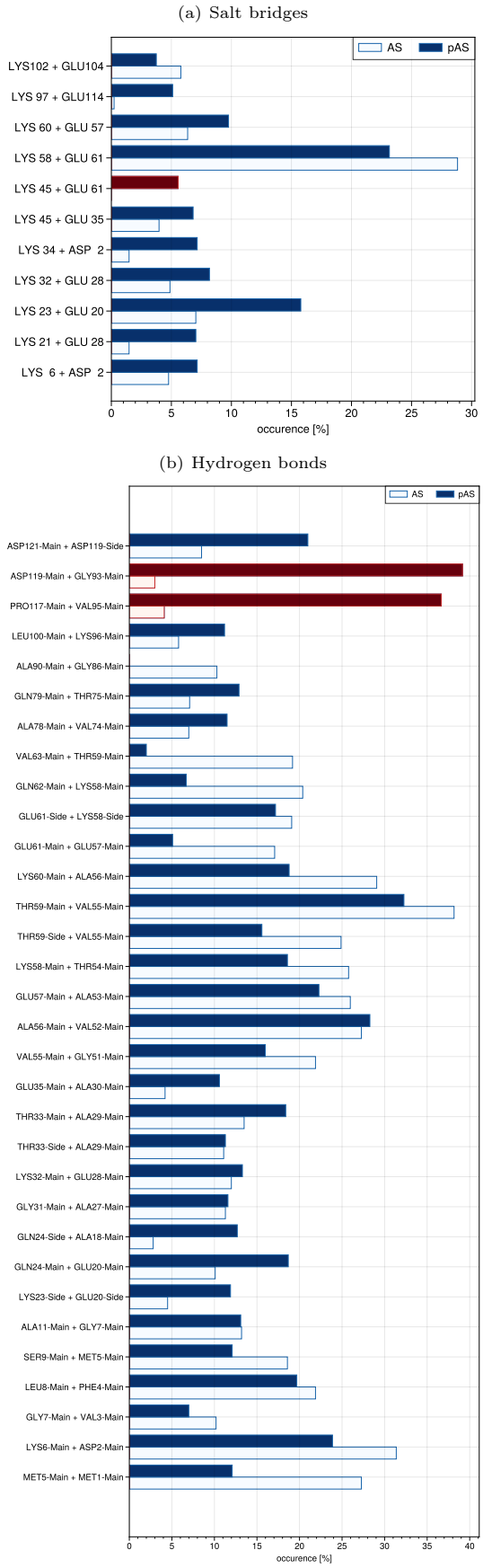


Figure 4. Occurence of intradomain (blue) and interdomain (red)) salt bridges (a) and H-bonds (b) in AS and pAS.

formational changes, becoming slightly more compact than the unmodified protein. The effect size may be ascribed to the fact that the added phosphate moiety points towards the solvent (within the limitations of the force field), and interacts, to a lesser extent, with counterions. Our calculations are consistent with the fact that CD spectra do not change significantly upon S129 phosphorylation in the unacetylated protein.[86] As the overall helicity in AS is low, the sensitivity of the calculated CD spectra may not be sufficient to register any changes in pAS that are small in terms of overall secondary structure, yet large when compared to AS. Addition caution must also be exerted when comparing results from unacetylated AS and physiological AS.[17] Finally, in the fibrils, the phosphate moiety might be solvated and stabilized by counterions, similarly to what we observed in aqueous solution for the monomer.

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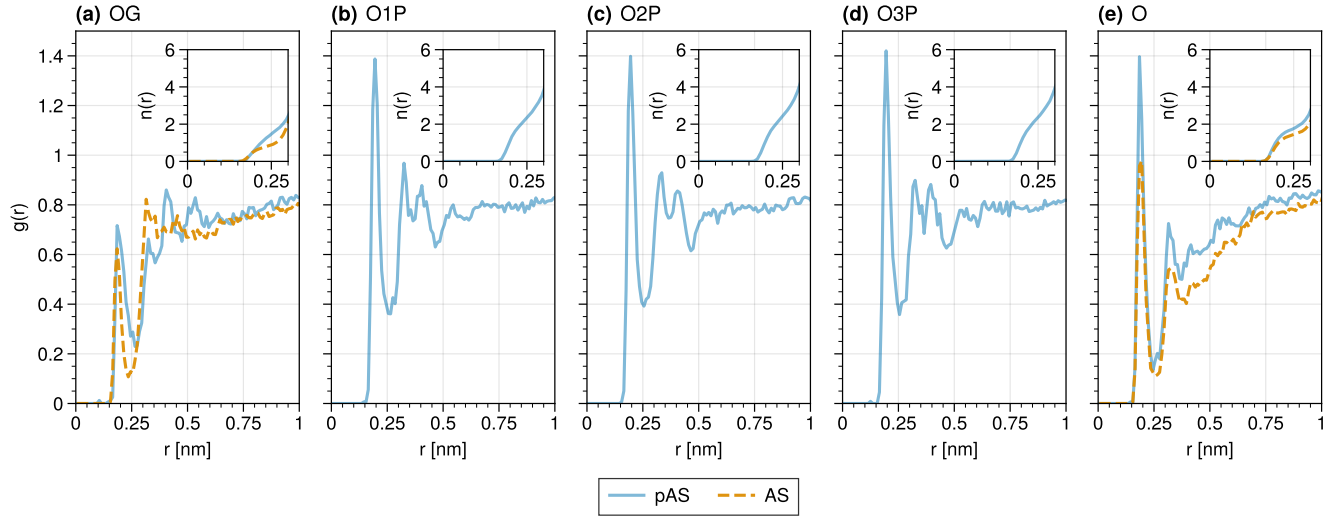

Figure 5. RDF ($g(r)$) of the oxygen atoms of residue 129 and water hydrogens (a-e). Compare the RDF for pAS (blue) and AS (orange) for the oxygen atom in the sidechain (a) and the carbonyl oxygen (e). (b)-(d) illustrate the RDF for the terminal phosphoryl oxygens. Insets show the integral of $g(r)$ up to 0.3 nm.

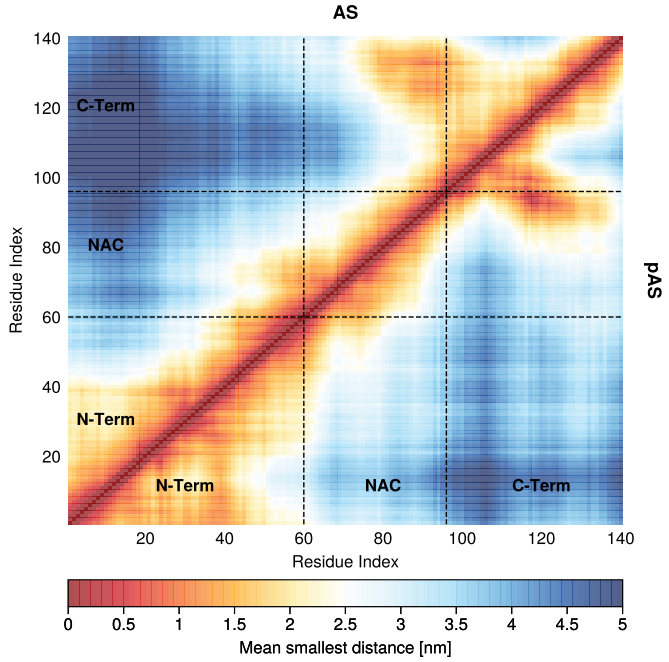

Figure 6. Contact maps in AS (triangle above) and pAS (triangle below).

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