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Supporting Information

Charge Reversal and Swelling in Saccharide Binding Polyzwitterionic Phenylboronic Acid-Modified Poly(4-vinylpyridine) Nanoparticles

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¹H/¹³C/¹¹B NMR and IR spectroscopy and calculation of the degree of quaternization The ratio of integrated signals of aliphatic to benzyl groups (marked in Scheme S1) should be theoretically 3:2 in QPVP-PBA, 3:1 in Q0.5PVP-PBA and 3:0.5 in Q0.25PVP-PBA. This was confirmed for all polymers (Figure S1).



Scheme S1. QPVP-PBA structure with marked hydrogens, which were used to calculate the degree of quaternization

The polymer QxPVP-PEO and the monomeric analog were dissolved in MeOD (10 g/L), and PVP was dissolved in 0.01M DCl (10g/L).



Figure S1. ¹H NMR spectra of PVP in 0.01M DCl.



Figure S1(a). ¹H NMR spectra of Q0.25PVP-PBA in CD₃OD





Figure S1(d). ¹³C NMR spectra of Q0.25PVP-PBA in CD₃OD



Figure S1(e). ¹³C NMR spectra of Q0.5PVP-PBA in CD₃OD

¹³C NMR (400 MHz, CD₃OD) δ (ppm): 148.20 (pyridinium C of position 'a'), 127.04 (pyridinium C of position 'b' & aromatic C of position 'i'), 163.67 (pyridinium C of position 'c'), 40.60 (methylene and methine C's of polymer backbone, position 'd'), 63.72 (benzylic C of position 'e'), 135.40 (aromatic C of position 'f'), 136.42 (aromatic C of position 'g'), 131.30 (aromatic C of position 'h'), 128.94 (aromatic C of position 'j'), 130.49 (aromatic C of position 'k'), 124.05 (pyridine C of position 'l'), 144.41 (pyridine C of position 'm'), 154.74 (pyridine C of position 'n').



Figure S1(f). ¹¹B NMR spectra of Q0.25PVP-PBA in CD₃OD

 $^{11}\text{B}\,\text{NMR}$ of Q0.5PVP-PBA in CD_3OD







Figure S1(h). ¹¹B NMR spectra of QPVP-PBA at different pH values



Figure S1(i). ¹¹B NMR spectra of Q0.5PVP-PBA at different pH values



Figure S1(j). ¹H NMR spectra of Q-P-PBA in CD₃OD



Figure S1(k). ¹³C NMR spectra of Q-P-PBA in CD₃OD



Figure S1(l). FTIR spectra of Q0.25PVP-PBA, Q0.5PVP-PBA and QPVP-PBA.



TGA

Figure S2. TGA and DSC curves (the same as in the main text but completed with the monomer)

The sharp peaks in the DSC curve of PBA at 170°C and 182°C correspond to the melting of PBA (mp. 158-162°C). Another sharp peak occurs at 421°C, which can be assigned to the melting of boron trioxide (trigonal B_2O_3 , with 450°C mp). The curve of the monomer shows similar peaks but not the polymers, in line with the crystalline and amorphous states of PBA and of the polymers, respectively.

The TGA of PBA above 315°C shows 45% weight loss, which we assigned to the loss of CH₃Br. Similar temperatures (around 300°C) of weight decrease were also detected by Adamczyk-Wozniak et al. [Adamczyk-Wozniak, A., et al. (2018) Dehydration of ortho-, meta-and para-alkoxy phenylboronic acids to their corresponding boroxines. European Journal of Inorganic Chemistry, 13, 1492-1498], although their compounds had –OR group instead of –CH₂Br. The DSC curve of the monomeric analog shows endothermic melting at 150°C folollowed by weight loss determined by TGA, which corresponds to water or to an OH group (possible boroxine formation). The monomeric analog likely releases this component right after phase transition (similarly to [1]). The second decrease at 250-320°C can be assigned to the release of methylpyridinium bromide. This is in agreement with the FTIR spectrum (signal around 3000 cm⁻¹ in the same temperature region). The weight loss above 320°C possibly correponds to the continuous formation of boron oxide accompanied by the release of water (H₂B₄O₇ above 300°C => 2 B₂O₃ + H₂O) and further decomposition of the benzene ring.



Figure S3. 3D FTIR spectrum of the monomeric analog

The monomeric analog likely formed boroxine after melting (150°C). According to [Morgan, A. B., Jurs, J. L., & Tour, J. M. (2000). Synthesis, flame-retardancy testing, and preliminary mechanism studies of nonhalogenated aromatic boronic acids: A new class of condensed-phase polymer flame-retardant additives for acrylonitrile–butadiene–styrene and polycarbonate. Journal of Applied Polymer Science, 76(8), 1257-1268.], boroxine formation is an endothermic process and therefore the endothermic peak after melting at 186°C likely corresponds to boroxine formation, accompanied by the exothermic release of water (200°C).

Potentiometric titration



Figure S4. Determination of pK_a from titration curves of the polymers and monomeric analog; (A) potentiometric titration curves, (B) linear regression of the variation of pK_a as a function of the degree of ionization alpha of the polymers and (C) of the monomeric analog.

Interaction with phosphate

QPVP-PBA was dissolved in 0.02M H₃PO₄, adding HCl to pH 2. During the titration with NaOH, the polymer remained soluble only below pH 5 and precipitated above this value. The polymer became soluble again above pH 11 approximately. In turn, after dissolution in 0.01M NaOH and titration with H₃PO₄, the solution was stable above pH 9 but precipitated below this value and became soluble again around pH 3. Precipitation in the neutral range of pH is likely caused by intermolecular binding of two different polymer chains through a molecule of hydrogen phosphate, which leads to cross-linking [Bosch, L. I. et al. (2004) Tetrahedron 60, 11175–11190.], [London, R. E.; Gabel, S. A. (1994) J. Am. Chem. Soc. 116, 2562–2569.]

A previous study has shown that boronic acids interact with phosphate structures, formed over a pH range during titration (phosphate, hydrogen phosphate and dihydrogen phosphate), and form complexes with various stability constants [Bosch, L. I. et al. (2004) Tetrahedron 60, 11175–11190.]. The stability of the phosphate complexes increases with the charge of the phosphate species. The highest values have been found in complexes involving PO₄³⁻, but these species are produced only at basic pH, in competition with hydroxide, so their contribution is small. [Bosch, L. I. et al. (2004) Tetrahedron 60, 11175–11190.] Another study reported the role of phosphate as a catalyst for hydroxide exchange on fluorophenylboronic acids [London, R. E.; Gabel, S. A. (1994) J. Am. Chem. Soc. 116, 2562–2569.]



Figure S5. Titration curve of QPVP-PBA polymer dissolved in 0.01M NaOH and titrated with 0.02M H_3PO_4 (red); empty circles indicate instability (phase separation) and black squares refer to blank titration



Scheme S2. Possible interactions between PBA and phospate

DLS and Zeta potential in MOPS buffer

Figure S7A shows the CONTIN distributions of apparent hydrodynamic radii from DLS measurements at scattering angle $\theta = 90^{\circ}$. The samples of Q-P-PBA, QPVP-PBA and Q0.5PVP-PBA in MOPS were transparent solutions. The scattering data indicate that some large scatterers were detected even in monomeric analog solution of Q-P-PBA, despite the low scattering intensity and the good solubility of the compound. QPVP-PBA and Q0.5PVP-PBA polymers exhibited a rather similar scattering behavior with a scattering intensity approximately 20 times higher than that of the sample of monomeric analog. All three solutions contained smaller assemblies with $R_{\rm H}$ under 10 nm and a few loose large aggregates, which represent only a minority population among scatterers. The solution of Q0.25PVP-PBA was turbid and scattered 280 times more than the solution of QPVP-PBA ($\theta = 90^{\circ}$). The monomodal distribution of hydrodynamic radius showed nanoparticles of $R_{\rm H}$ around 100 nm (this sample is likely not in equilibrium and phase-separated slowly). The DLS of the QPVP-PBA polymers used for fluorescence measurement was also measured using Zetasizer equipment at scattering angle $\theta = 173^{\circ}$. Intensity and number-based distribution diagrams are shown in Figure 7B in which the size of nanoassemblies increased with the decrease in the degree of modification and thus with the increase in the hydrophobicity of polymer. The zeta potentials of the dialyzed solutions were 37 ± 3 mV, 43 ± 1 mV and 49 ± 2 mV for QPVP-PBA, Q0.5PVP-PBA and Q0.25PVP-PBA, respectively. This indicates that the nanoparticles are stabilized electrostatically.



Figure S6. CONTIN DLS distribution of apparent hydrodynamic radii $R_{\rm H}^{\rm app}$ at (A) 90° and (B) 173° angles of QPVP-PBA aggregates and of the monomeric analogue in MOPS buffer solution

Potentiometric titration with saccharides



Figure S7. Potentiometric titration curves of QxPVP-PBA after saccharide addition and variation of pKa as a function of the degree of ioniziation (alpha fitted linearly)

DLS after fructose addition



Figure S8. CONTIN DLS intensity-averaged distribution of hydrodynamic radii ($R_{\rm H}$) of QxPVP-PBA nanoassemblies and of QxPVP-PBA nanoassemblies after fructose addition