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Supporting Information for: Softening of Phospholipid Membranes by the Adhesion of Silica Nanoparticles - As Seen by Neutron Spin-Echo (NSE)

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I. SAXS

SAXS measurements have been performed using a SAXSess mc^2 system (Anton Paar GmbH, Graz, Austria). The obtained curve could be described with the form factor of spheres and a radius of 8.36 nm was obtained (see fig. S1).

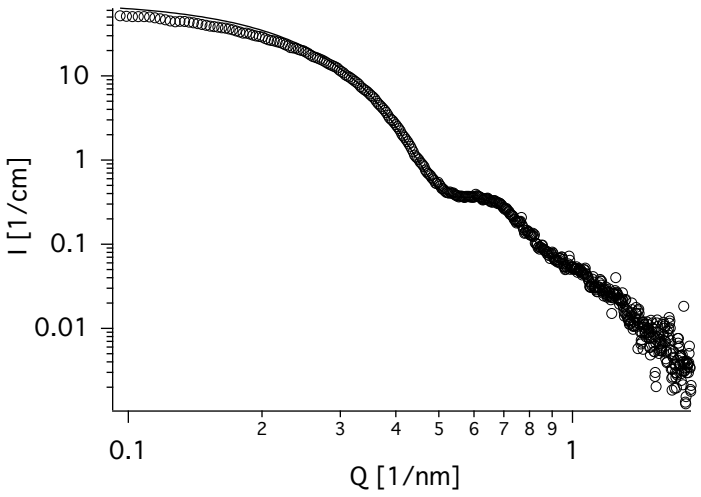

FIG. S1. SAXS data of pure NPs.

II. SANS

The scattering length density of the outer NP shell is related to the volume fraction of NPs in the shell x_{NP} by

$$SLD_{NP,shell} = x_{NP} SLD_{NP} + (1 - x_{NP}) SLD_{solv}, \tag{S1}$$

where SLD_{solv} and SLD_{NP} are the scattering length densities of solvent and nanoparticles. Assuming a constant number of NPs per outer vesicle area a_{NP}, x_{NP} is given by

$$x_{NP} = \frac{a_{NP} A_{Ves} V_{NP}}{V_{shell}}, \tag{S2}$$

where $A_{Ves} = 4\pi R_{Ves}^2$ is the outer surface Area of a vesicle, $V_{NP} = 4\pi/3 R_{NP}^3$ is the volume of a NP and the volume of the outer NP shell is given by

$$V_{shell} = \frac{4\pi}{3}((R_{Ves} + D_{NP})^3 - R_{Ves}^3), \tag{S3}$$

where $D_{NP} = 2R_{NP}$. For given volume fractions of NPs ϕ_{NP} and phospholipids ϕ_{Ves} and a phospholipid bilayer thickness d, a_{NP} is given by

$$a_{NP} = \frac{{}^1N_{NP}}{{}^1N_{Ves} A_{Ves}} = \frac{\phi_{NP}}{\phi_{Ves} A_{Ves} R_{NP}^3}(R_{Ves}^3 - (R_{Ves} - d)^3), \tag{S4}$$

Where ${}^1N_x$ is the particle number density of x. Inserting eqs. (S3) and (S4) in eq. (S2), we obtain

$$x_{NP} = \frac{\phi_{NP}}{\phi_{Ves}} \frac{R_{Ves}^2 d - R_{Ves} d^2 + 1/3 d^3}{R_{Ves}^2 D_{NP} + R_{Ves} D_{NP}^2 + 1/3 D_{NP}^3} \tag{S5}$$

or expressed in terms of particle number densities

$$x_{NP} = \frac{{}^1N_{NP} D_{NP}^3}{{}^1N_{Ves} 8} \frac{1}{R_{Ves}^2 D_{NP} + R_{Ves} D_{NP}^2 + 1/3 D_{NP}^3}. \tag{S6}$$

If the vesicles are polydisperse (but the NPs are not and d is constant) and we assume a constant $\langle a_{NP} \rangle$, calculated according to eq. (S4) from the average values, then for vesicles with a specific radius we obtain

$$x'_{NP} = \langle a_{NP} \rangle V_{NP} \frac{R_{Ves}^2}{R_{Ves}^2 D_{NP} + R_{Ves} D_{NP}^2 + 1/3 D_{NP}^3}. \tag{S7}$$

To give an example, for a volume fraction of phopholipids of 0.001 forming vesicles of 45 nm average outer radius with a bilayer thickness of 3.6 nm and a volume fraction of

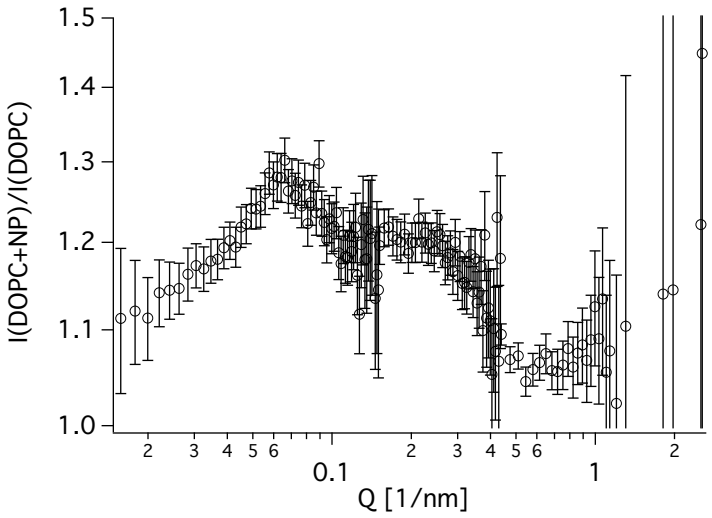

FIG. S2. SANS intensity of DOPC vesicles with NPs divided by that of pure DOPC vesicles. The peak at about 0.06 1/nm is due to the shift of the form factor minimum, the second peak at 0.2 1/nm may be attributed to a weak correlation peak between the NPs on the vesicle.

3.95E-4 of NPs with a radius of 8.34 the number of NPs per vesicle is ${}^1N_{NP}/{}^1N_{Ves} = \frac{3.95\text{E}-4/(8.34\text{ nm})^3}{0.001/((45\text{ nm})^3-(45\text{ nm}-3.6\text{ nm})^3)} = 13.73$. The average number of NPs per area is $\langle a_{NP}\rangle = \frac{13.73}{4\pi(45\text{ nm})^2} = 5.4\text{E}-4\text{ nm}^{-2}$. With eq. (S7), using the previously calculated $\langle a_{NP}\rangle$ we obtain a contrast $SLD_{NP,shell}$ that changes from 6.168E-4 (55 nm vesicle) to 6.177E-4 (45 nm) to 6.191E-4 1/nm^2 (35 nm), always using 6.33E-4 1/nm^2 for the solvent (D_2O) and 3.58E-4 1/nm^2 for the NPs. These changes are small enough to safely ignore them and use the average contrast.

TABLE S I. Parameters from SANS fit, using eq. (3) with eqs. (1) and (4); R is the outer radius of the vesicle, if NPs are present another outer shell with thickness $2R_{np}$ is present, SD/R is the standard deviation, divided by the radius, ϕ_{ves} and ϕ_{np} are the volume fractions of the phospholipid bilayer and the NPs, respectively, R_{np} is the radius of the NPs, $d_{bilayer}$ is the thickness of the phospholipid bilayer, SLD_x is the scattering length density of the solvent (solv), the NPs (np) and the bilayer. R, SD and $d_{bilayer}$ are the only free parameters. Both curves were fitted simultaneously with R, SD and $d_{bilayer}$ as shared parameters.

	DOPC	DOPC + NP
R [nm]	43.48	43.48
SD/R	0.2	0.2
ϕ_{ves}	0.0011	0.0011
ϕ_{np}	0	0.00042
R_{np} [nm]	-	8.36
$d_{bilayer}$ [nm]	3.6	3.6
SLD_{solv} [1/nm^2]	0.000633	0.000633
SLD_{np} [1/nm^2]	0.000358	0.000358
$SLD_{bilayer}$ [1/nm^2]	3.01e-05	3.01e-05

III. TEM

Some free NPs can be seen in the images, but it seems that the vesicles have a tendency to adsorb on the grid and thereby releasing the NPs Furthermore, some oligo lamellar vesicles can be seen, the formation of which may be induced by shear forces during the blotting process. That some of the vesicles are destroyed during sample preparation is also shown by the fact that the remaining vesicles are loaded with more NPs than there should be from a stochiometric point of view. The ratio of NPs to vesicles in the solution is 12 but the vesicles which are seen in cryo-TEM are loaded with significantly more NPs. This is probably due to the destruction of a significant fraction of the vesicles by the shear forces applied in the sample preparation process, as can be seen from the NP/vesicle ratio being much higher than it should be (see fig. S3) with regard to the sample composition and the SANS measurements. Even though, this prohibits a quantitative analysis, the images still qualitatively show that there are NP decorated vesicles in the solution and that these vesicles mostly retain their size and shape.

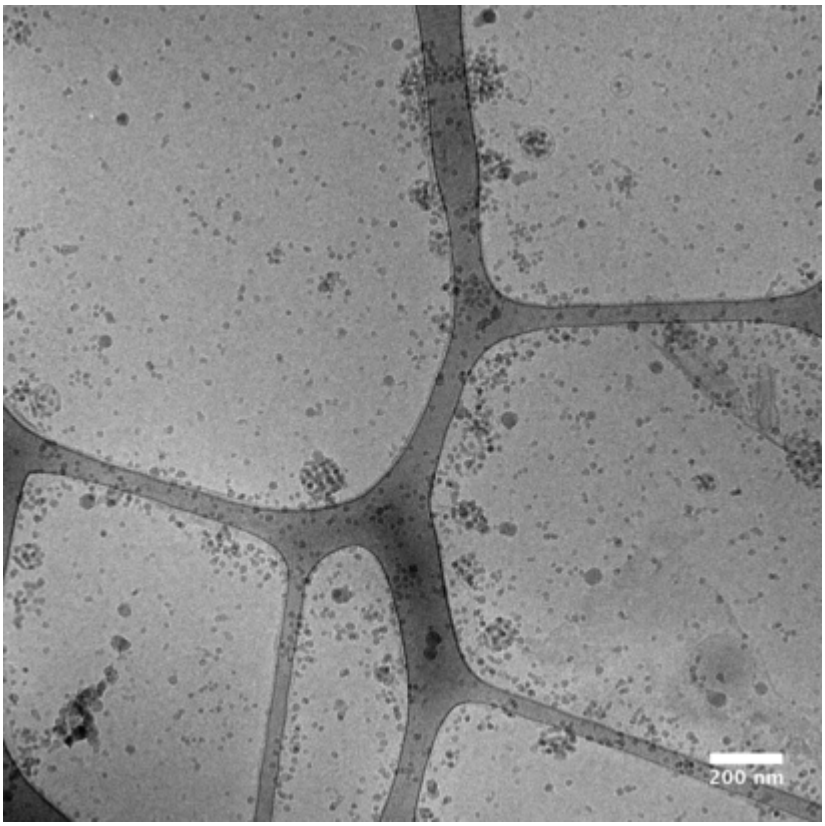

FIG. S3. The majority of the NPs is found near the grid despite their negative charge.

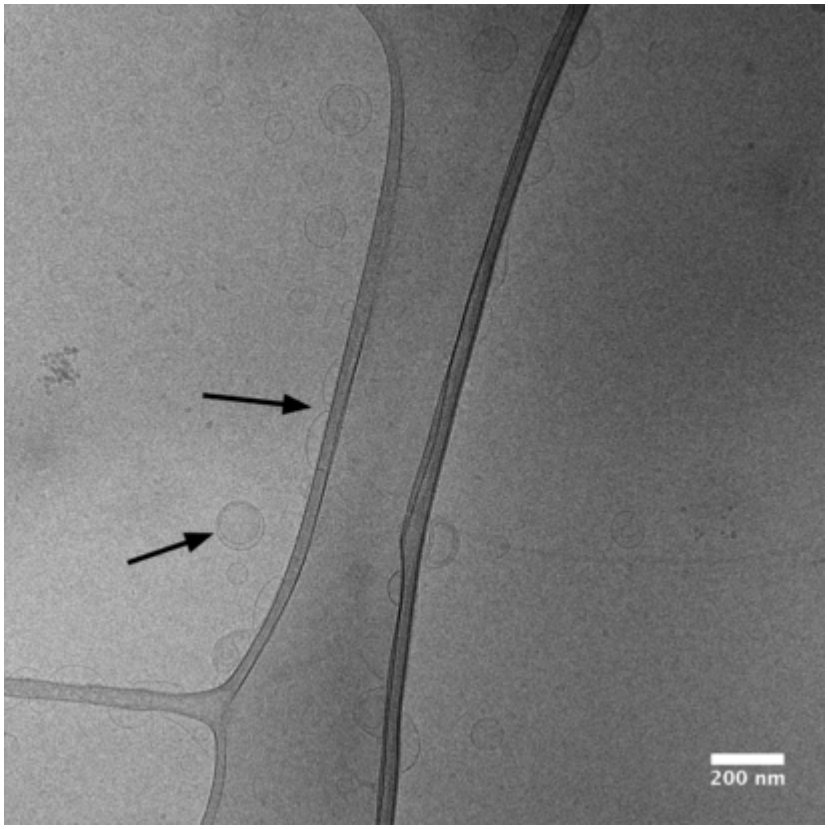

FIG. S4. The vesicles adsorb on the grid and are destroyed (upper arrow). The shear forces applied in the sample preparation process induce the formation of some non-unilamellar vesicles (lower arrow).

IV. DLS

The theoretical curve in fig. 4 has been calculated as follows:

$$g^2(t) - 1 = 0.34(0.5 \exp(-2 \cdot 0.357 \text{ Å}^2/\text{ns}\, Q^2 t) + 0.5 \exp(-2 \cdot 1.65 \text{ Å}^2/\text{ns}\, Q^2 t)), \qquad \text{(S8)}$$

0.357 Å^2/ns and 1.65 Å^2/ns are the diffusion coefficients obtained from measuring vesicles and NPs alone.

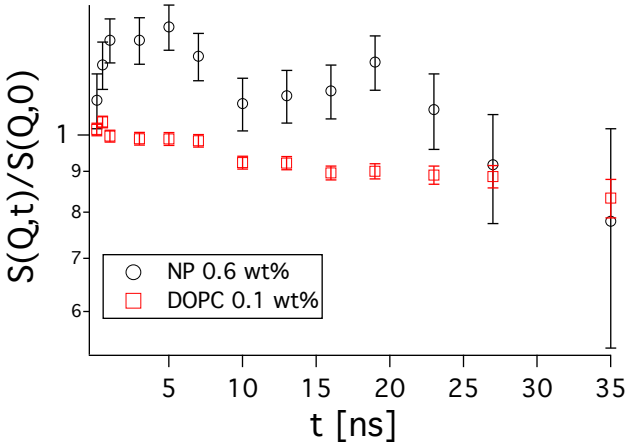

FIG. S5. NSE data of pure NPs, c=0.6 wt% (black circles) and pure DOPC vesicles, c=0.1 wt% at $Q = 0.8$ 1/nm with the same acquisition time. Even at much higher concentrations, the statistics for the pure NPs are quite bad compared to the vesicles as can be seen by the large error bars. At the actual sample composition the signal from the vesicles is roughly 20 times stronger than that from the NPs. Therefore and because of the data from DLS which suggests that the NPs are adsorbed, it is safe to ignore the contribution of free NPs in the analysis of NSE data. (JNSE)

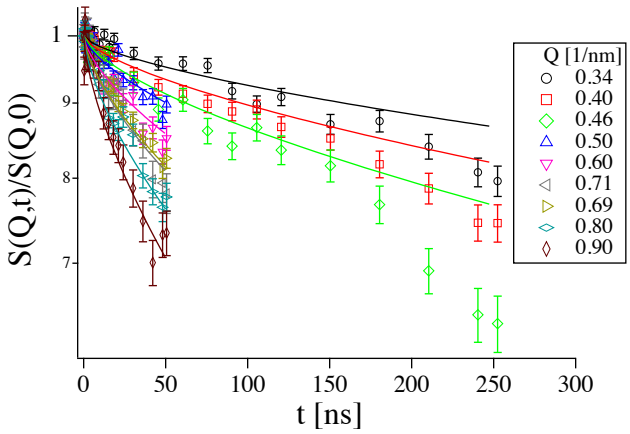

FIG. S6. NSE data of pure vesicles, fits using eq. (12) with a single set of parameters, but setting $D = 0$. At long times, deviations become apparent. (IN15)

V. NSE

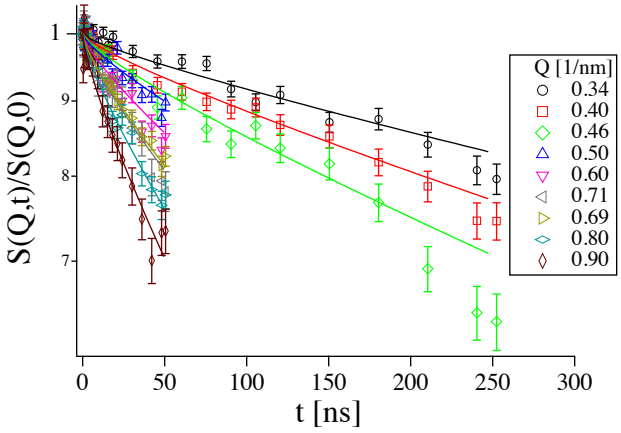

FIG. S7. NSE data of pure vesicles, fits using eq. (12) with a single set of parameters. (IN15)