Supplementary Information

Solid-State Nanopore Time-of-Flight Mass Spectrometer

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The Supplementary Information includes:

1. Supplementary Figures (Figs. S1-S9)

2. Supplementary Table (Tab. S1)

3. Supplementary references

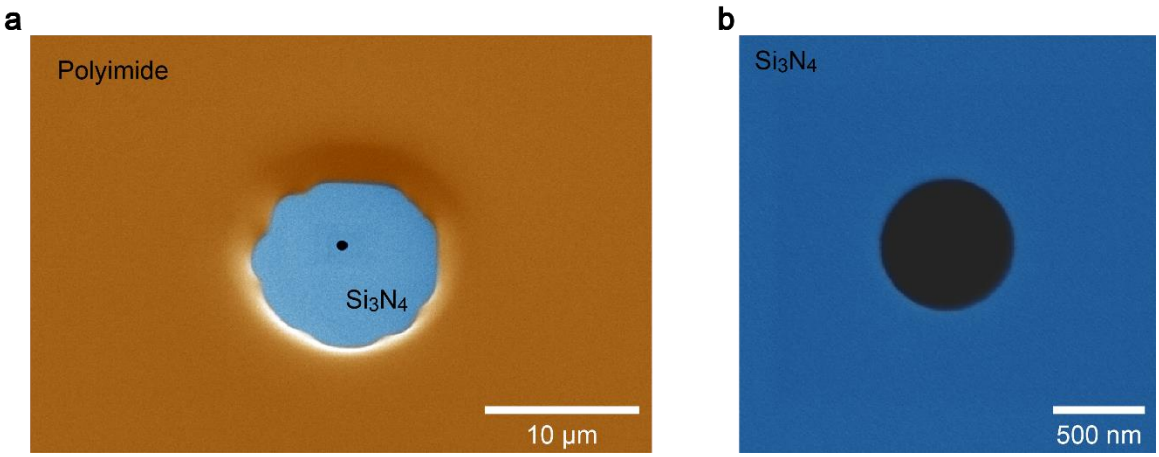

Figure S1. Structure of a polyimide-coated nanopore. **a,** False-colored scanning electron micrographs of a nanopore of diameter 700 nm sculpted in a 50 nm-thick Si_3N_4 membrane. The entire membrane surface except the 10 μm area around the pore was coated with 5 μm-thick polyimide layer. **b,** A magnified view of the nanopore.

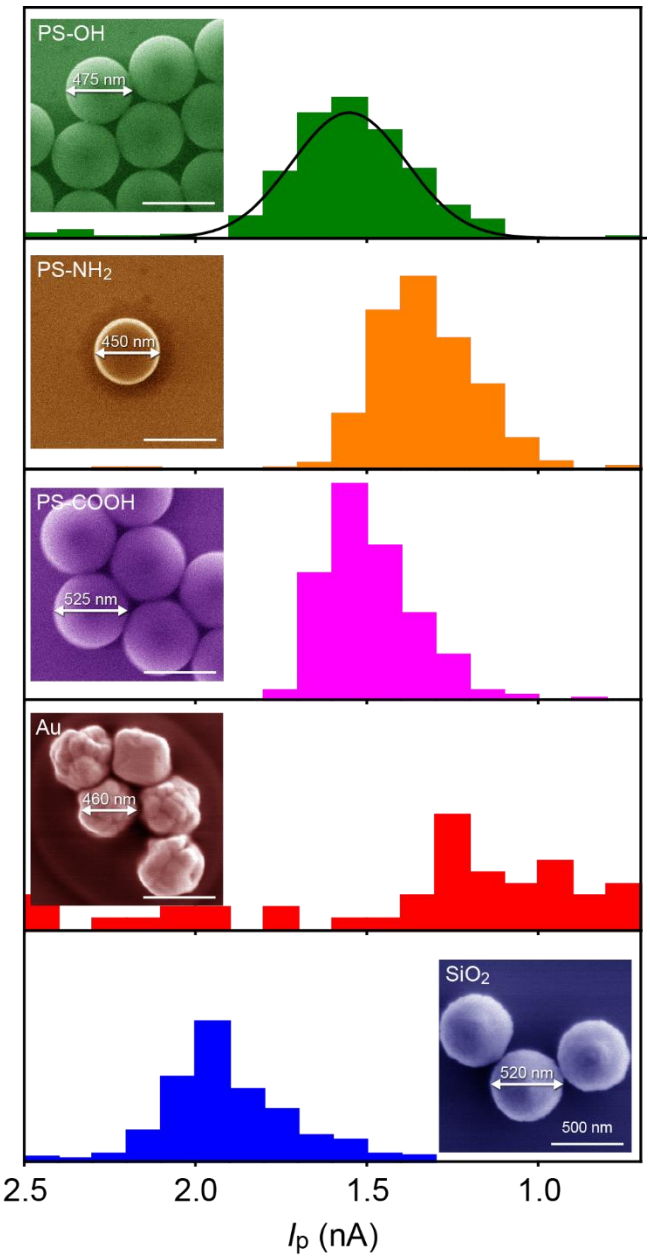

Figure S2. Histograms of the resistive pulse height I_p obtained for functionalized polystyrene (PS) nanobeads having OH- (green), NH_2- (orange), and COOH-groups (purple) as well as Au (red) and SiO_2 nanoparticles (blue). Solid curve is Gaussian fit to the histogram that provided the average I_p for each type of particles.

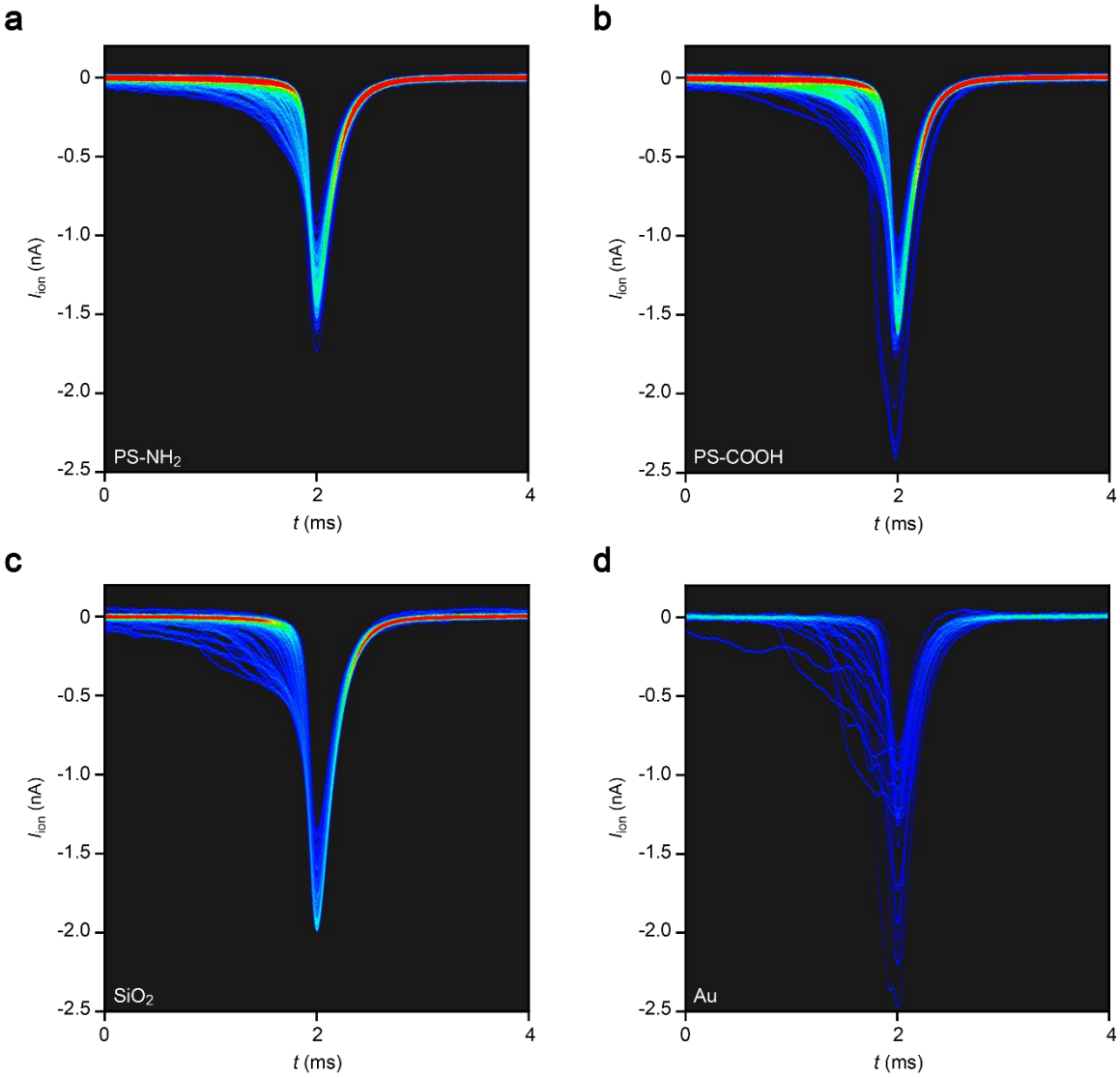

Figure S3. a-d, Two-dimensional histograms of resistive pulses obtained with a 700 nm-sized nanopore in a 50 nm-thick Si_3N_4 membrane for 450 nm-sized NH_2-functionalized polystyrene (PS) nanoparticles (a), 525 nm-sized COOH-decorated PS (b), 520 nm-sized SiO_2 nanoparticles (c), and 460 nm-sized Au nanoparticles (d). Open pore current is offset to zero. 2 ms before and after the ionic current minima are shown. Whereas the pulse onsets demonstrate variety of trace shapes, the tails are quite regular, which is typical of particle trajectory-dependence of the ionic current blockade in low-aspect ratio nanopores.[S1]

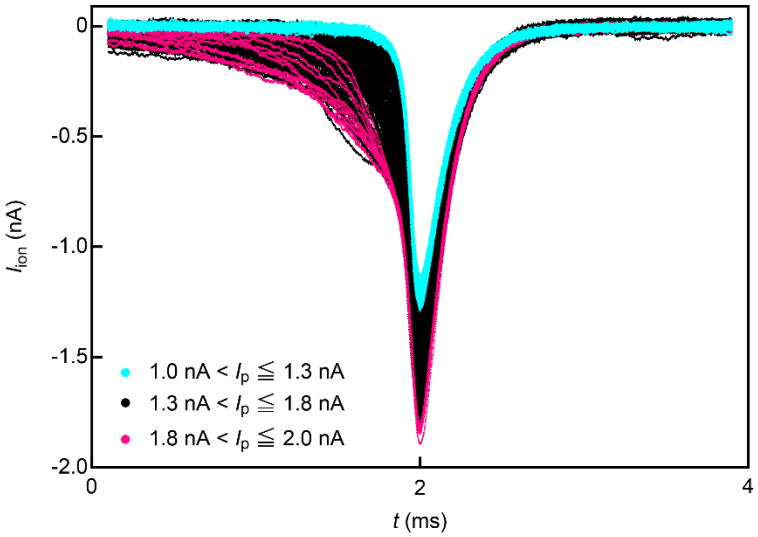

Figure S4. Particle trajectory-dependent ionic current blockade for PS-OH in a 700 nm-sized nanopore. Small pulses show less scattering in the trace motif that correspond to particle translocation through axial positions (sky blue). On the other hand, large pulses exhibit various trace forms at the onsets ascribed to off-axial translocation of the polymeric particles with random incident angles at the capture stage.[S1-S3]

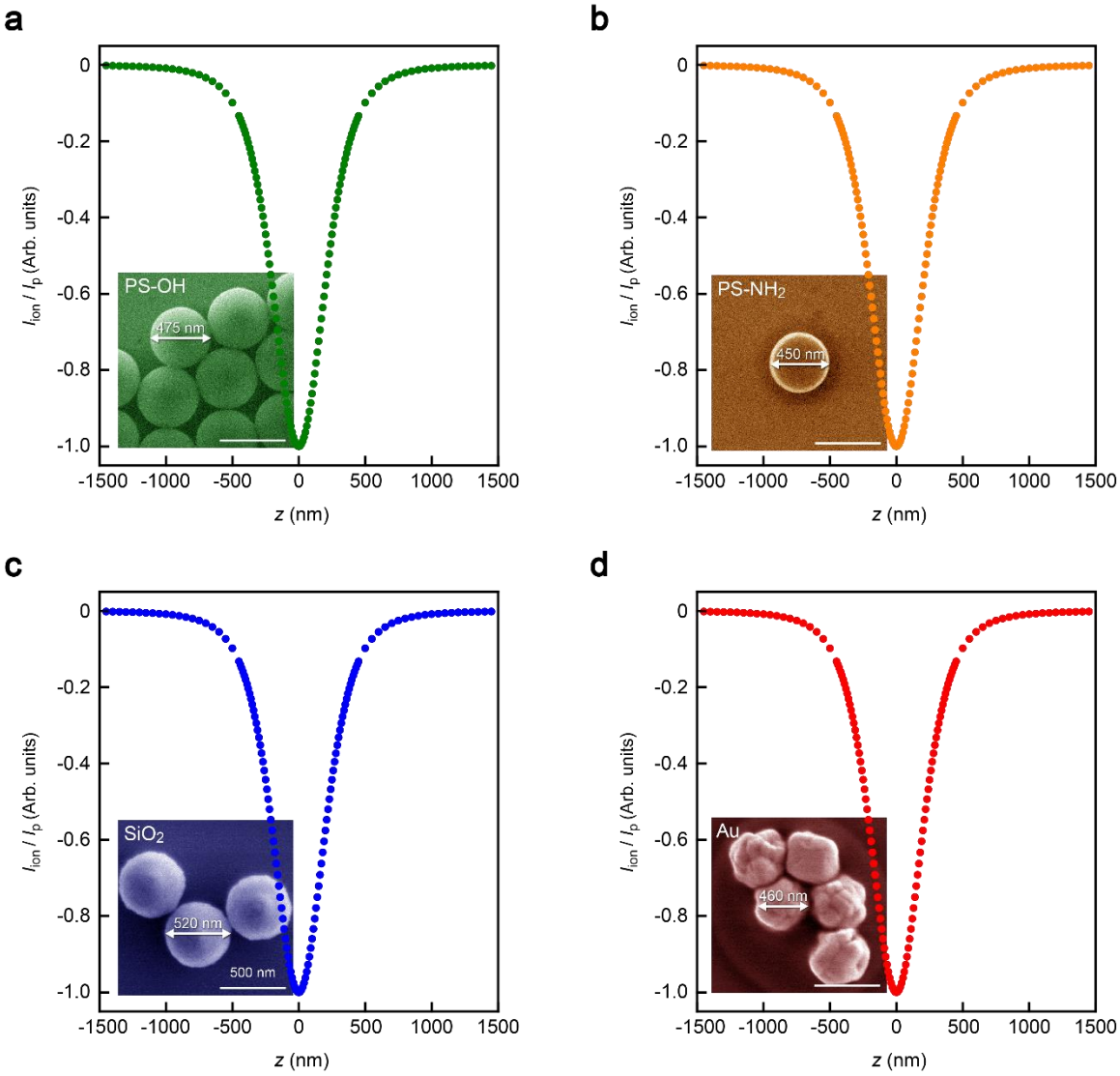

Figure S5. a-d, Theoretical resistive pulses obtained using COMSOL for 475 nm-sized OH-functionalized polystyrene (PS) nanoparticles (a), 450 nm-sized NH_2-decorated PS (b), 520 nm-sized SiO_2 nanoparticles (c), and 460 nm-sized Au nanoparticles (c) passing through a 700 nm-sized nanopore in a 50 nm-thick Si_3N_4 membrane in 0.2 x PBS under 0.1 V. The cross-membrane ionic current I_{ion} is normalized by the pulse height I_p. Lateral axis z denotes the vertical position of the particles along the pore axis, which is set to zero at the membrane center.

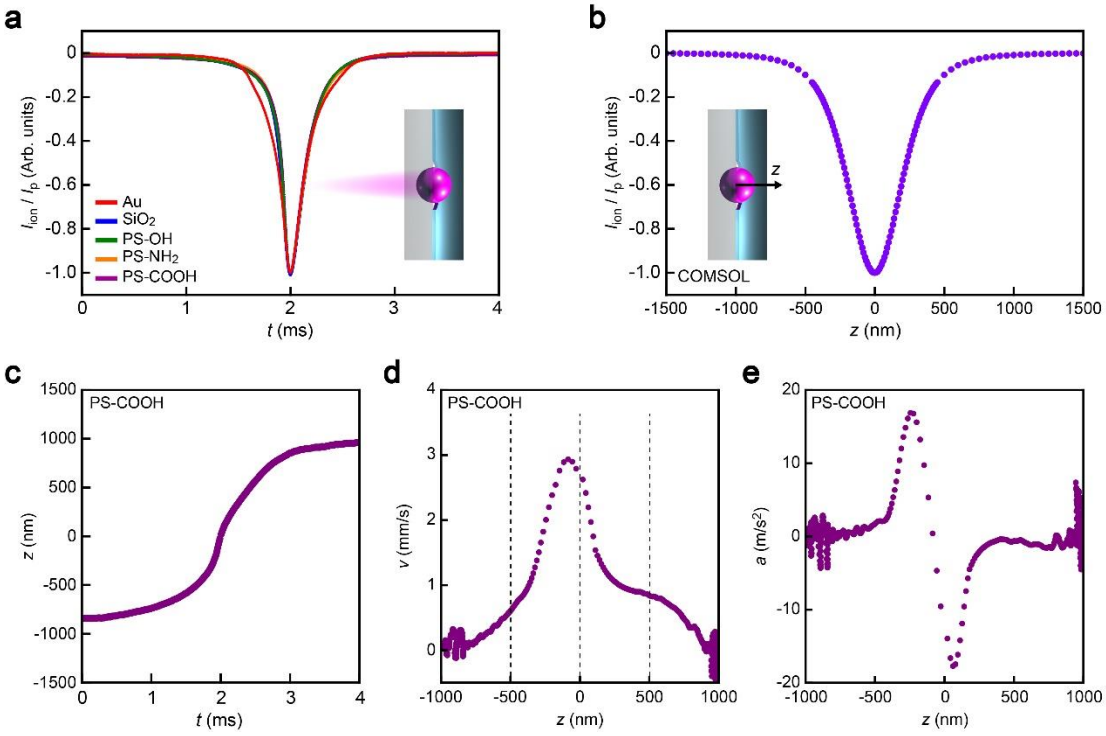

Figure S6. Single-particle dynamics analysis. **a,** Normalized resistive pulses of 500 nm-sized nanoparticles. Base current is offset to zero. **b,** COMSOL-derived resistive pulse of 525 nm-sized nanoparticle modeling the PS-COOH. **c,** The position *z* of the center of the PS-COOH nanoparticle deduced from the data in (a) and (b). **d-e,** The velocity *v* (d) and the acceleration *a* (e) obtained by numerical derivation of the *z* – *t* curve displayed in (c).

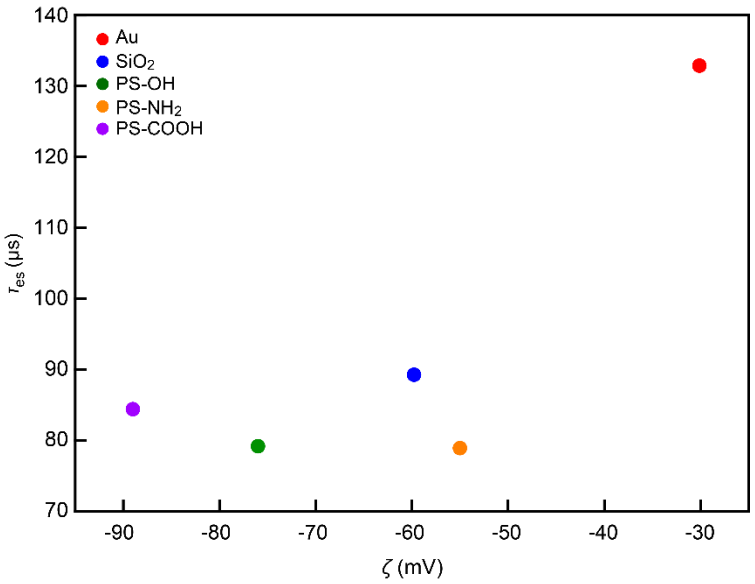

Figure S7. Time constant τ_{es} of the exponential decay of the particle velocity at during the escape from the 700 nm-sized Si_3N_4 nanopore plotted as a function of the particles' zeta-potential ζ.

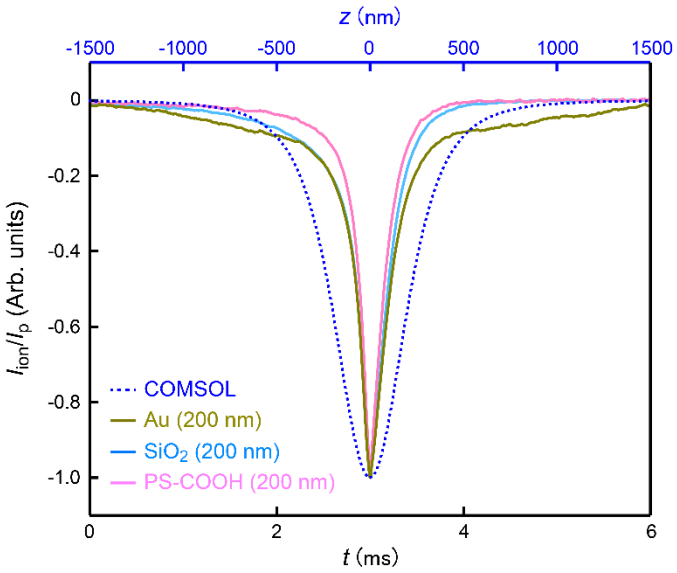

Figure S8. Resistive pulses obtained for 200 nm-sized nanoparticles. The open pore current is offset to zero and the ionic current I_{ion} is normalized by the pulse height I_p for both the experimental (solid; I_{ion}/I_p - t) and simulated (dashed; I_{ion}/I_p - z) curves. Color coding denotes the materials of the nanoparticles as: dark yellow = Au; sky blue = SiO_2; pink = carboxylated polystyrene (PS-COOH). The experimental I_{ion}/I_p curves are the average of 569, 1982, and 1770 pulses for the Au, SiO_2, and PS-COOH nanospheres, respectively.

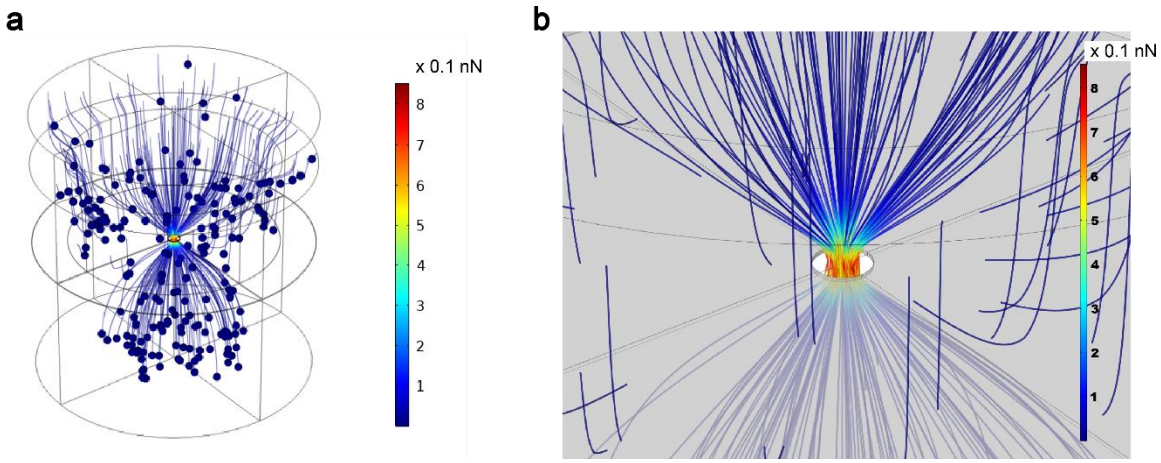

Figure S9. **a,** Electrophoretic force on translocating 460 nm-sized nanoparticles through a 700 nm-diameter nanopore estimated by a three-dimensional finite element analysis using COMSOL multiphysics 5.4 that simultaneously solved Poisson equation, continuity equation at steady-state current, Nernst-Planck equation, and Naiver-Stokes equation. The surface charge density on the particles were – 20 mC/m^2. **b,** A close view of the nanopore in (a). The force on the particles is relatively large amounting about 0.85 nN when the particles are in the nanopore, which suggests minor influence of Brownian motions during the fast transits through the channel. The simulations were, however, performed under a steady-state condition where the total force is defined to be zero, i.e. complete balance of the electrophoretic and hydrodynamic drag forces. Therefore, it is not possible to assess the actual influence of the viscous drag force from this result. It would call for further simulations under non-steady-state conditions to dissect the physical mechanism underlying the decelerated single-nanoparticle motions in the post-translocation regime.

Table S1. Physical parameters of test particles.

Particle	d_p (nm)	ρ_d (kg/m^3)	*m* (pg)	ζ (mV)
PS-OH	475	1040	0.058	-76
PS-NH_2	450	1040	0.050	-55
PS-COOH	525	1040	0.078	-89
	200	1040	0.004	N/A
SiO_2	520	2196	0.16	-60
	200	2196	0.09	N/A
Au	460	19320	7.9	-30
	200	19320	0.81	N/A

References

S1. Tsutsui, M., He, Y., Yokota, K., Arima, A., Hongo, S., Taniguchi, M., Washio & T., Kawai, T. Particle trajectory-dependent ionic current blockade in low-aspect-ratio pores. *ACS Nano* **10**, 803-809 (2016).

S2. Smythe, W. R. Off-Axis Particles in Coulter Type Counters. *Rev. Sci. Instrum.* **43**, 817 (1972). DOI: https://doi.org/10.1063/1.1685770

S3. Qin, Z., Zhe, J. & Wang, G. –W. Off-Axis Position, Shape, Orientation and Entry Position on Resistance Changes of Micro Coulter Counting Devices. *Meas. Sci. Technol.* **22**, 054804 (2011). DOI: 10.1088/0957-0233/22/4/045804