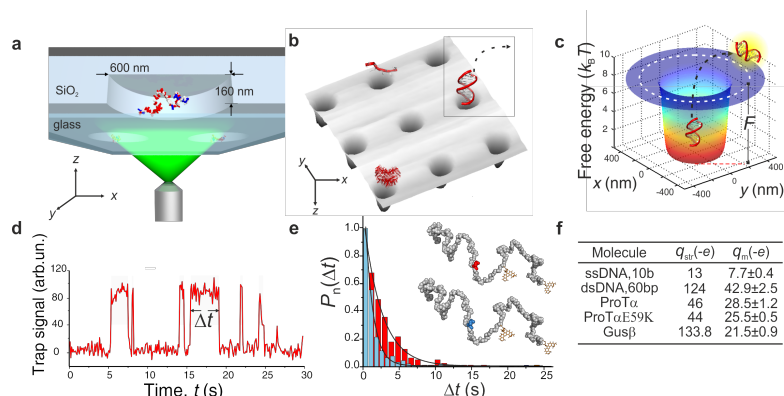


## Single-molecule electrometry

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Electrical charge is a fundamental property of biomolecules, strongly influencing their function [1] and stability. We demonstrate for the first time a high-precision ( $<1e$ ), measurement of the electrical charge of biomolecules in solution. The method is based on parallel, external field-free trapping [2] at an unprecedentedly low estimated sensitivity of yoctomoles (1-10 molecules). Our single molecule trap is created in a fluid-filled gap between two charged walls. Nanoscale patterning of one of the surfaces leads to a modulation of the local electrostatic potential, creating a deep thermodynamic potential well for a like-charged entity (Fig.a-b). In our new method "Escape Time Electrometry" (ETe) [3] we show for the first time stable trapping of biomolecules in solution, for tunable timescales ranging from hours to milliseconds. The depth of the well,  $F$ , experienced by a charged molecule is linearly proportional to its effective charge  $q_m$  (Fig.c). A molecule undergoing Brownian motion will reside in a trap for a time ( $t_{esc}$ ) given by Kramer's analytical expression,  $t_{esc} = t_r \exp(F/k_B T)$ , where  $t_r$  is a relaxation time that depends on the diffusion coefficient of the molecule. When occupied by a fluorescently-labelled molecule the optical intensity of the trap region is high (Fig.d). The duration of the intensity bursts ( $\Delta t$ ) follows an exponentially decaying probability distribution  $P_n(\Delta t)$ , which is fitted to extract  $t_{esc}$ , yielding information on the well depth and thus directly giving the effective charge  $q_m$ . Finally,  $q_m$  can be theoretically modelled and related to the molecule's known structural charge ( $q_{str}$ ); the table in Fig.f summarizes a few representative results.



The measured charge of DNA molecules is in remarkable agreement with existing theoretical predictions [4] and suggest that ETe can serve to readout the inter-nucleotides spacing of a nucleic acid molecule or polyelectrolyte. The study of the enzyme Gusβ suggests substantial regulation of the structural charge in a globular molecule [5], while our measurements on ProTa, a disordered one-dimensional polypeptide, provides unique insight into the charge renormalizing behavior of short, strongly charged segments within the molecule. Crucially, the exponential dependence of  $t_{esc}$  on the charge of the molecule permits us to distinguish between two ProTa variants that differ by a mutation of a single amino acid (E59K, 4% of the structural charge) (Fig.e). The Electrometry measurement can also be performed on a single molecule in real time, with the potential of detecting charge fluctuations, making ETe a new tool for ultrasensitive, rapid structural studies on biological macromolecules in the fluid phase.

[1] Perutz, *Science*, **1978**, 201:1187-1191. [2] Krishnan et al., *Nature*, **2010**, 467:692-695. [3] Ruggeri et al., 2017; *Nature Nanotechnology*, **2017**, 12:488-495 [4] Manning, *Journal of Chemical Physics*, **1969**, 51:924-& 492. [5] Ninham, Parsegian, *Journal of Theoretical Biology*, **1971**, 31:405-428