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A quantitative model of temperature actuated DNA origami nanocaliper constructs

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Abstract

Manipulating the temperature of an incorporated gold nanoparticle can be used to actuate DNA origami nanocalipers. We develop a physical model of this system that uses partition function analysis to predict the probability that the nanocaliper is open at a given temperature. The model agrees well with experimental data, and the comparison between model and experimental data reveals surprising insights into the nanocaliper-nanoparticle system. Additionally, the model predicts experimental conditions that allow the actuation temperature of the nanocaliper to be tuned over a wide range of temperatures from 20°C to 60°C.

Motivation

Experimental Motivation

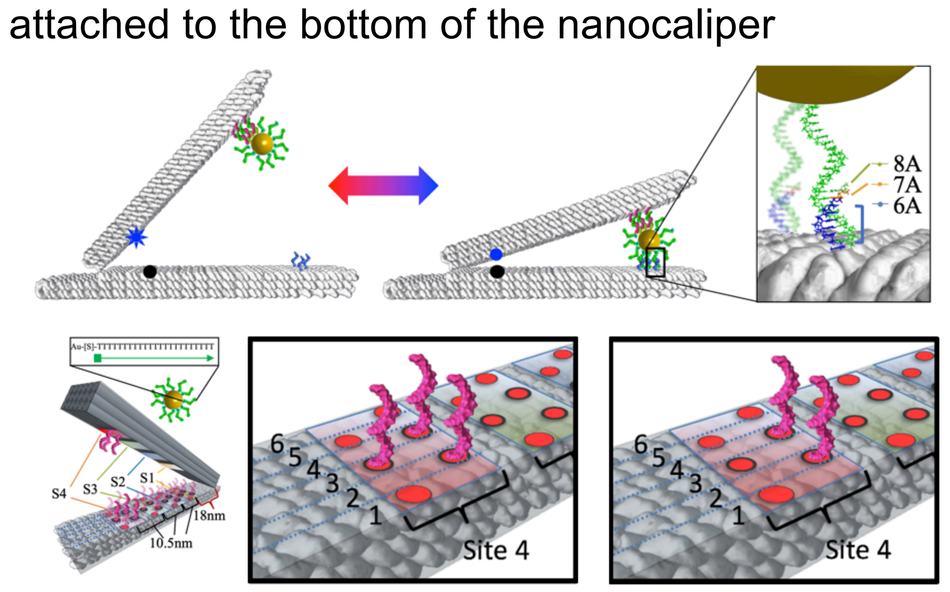
- General motivation: to make nanoscale machines
- DNA origami allows design of nanoscale objects
- Actuation lets these objects function as parts of a machine [1].
  - Nanocaliper actuation has been achieved previously by changing buffer conditions [2], whereas this method uses a temperature change.
  - The nanoparticle may allow local heating and may affect overhang binding free energy.

Model Motivation

- Deduce microscopic properties of the physical system
- Use model to optimize design in large parameter space

Physical System

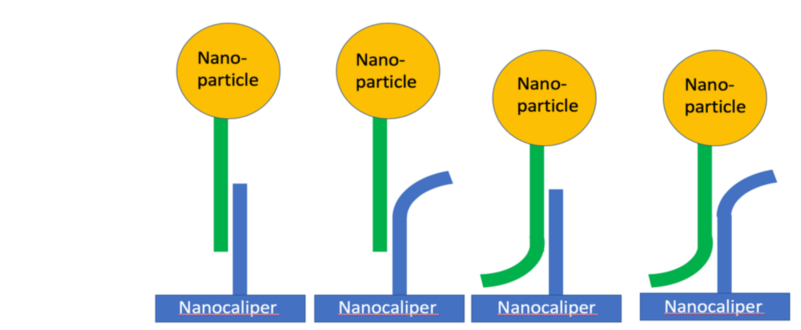
- A gold nanoparticle is attached to the top of a nanocaliper.
- PolyT ssDNA strands with 23 bases are attached to the surface of the nanoparticle.
- Complementary polyA strands with 6 to 8 bases are attached to the bottom of the nanocaliper



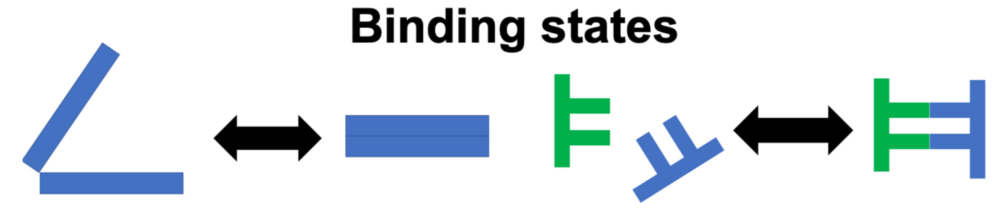
"trivalent" case "bivalent" case

Model

- The model uses a partition function analysis to calculate the probability that the nanocaliper is open.
- The partition function takes into account the illustrated binding states and free energy shifts.



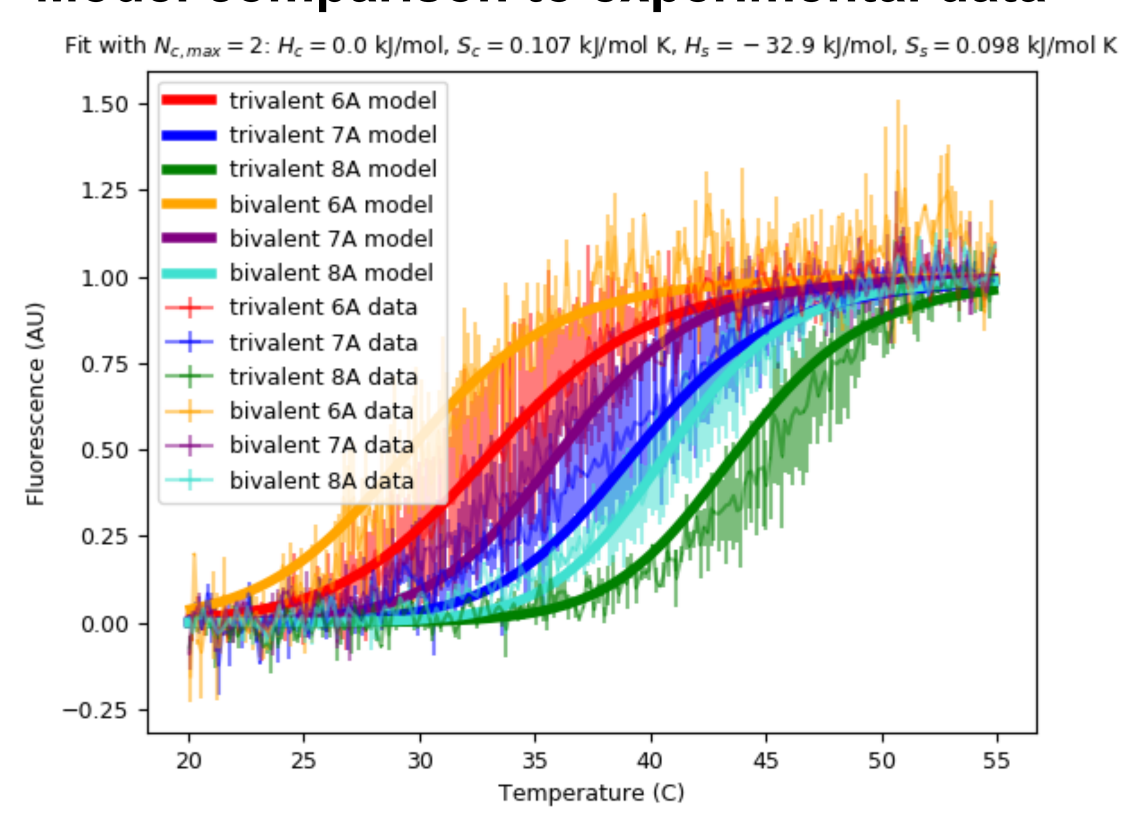
Binding states



$\Delta G = \Delta H_C + T\Delta S_C$ $\Delta G = \Delta H_S + T\Delta S_S$

Free energy shifts

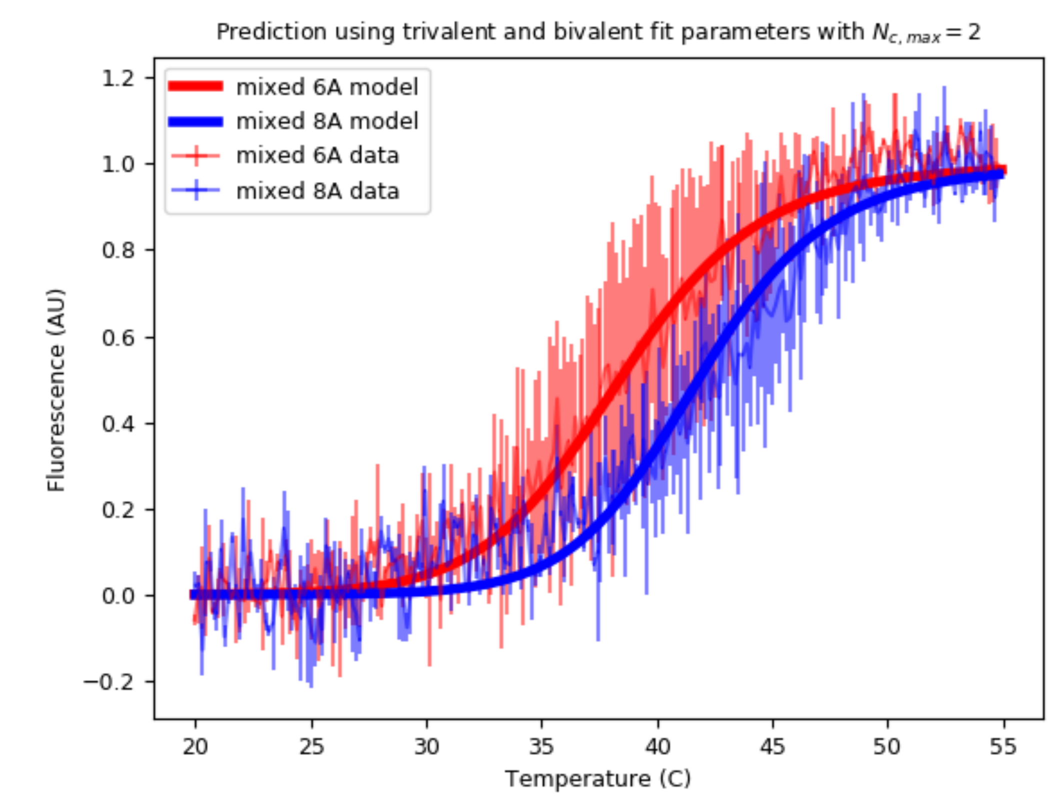
Model comparison to experimental data



- Above: model simultaneously fit to trivalent and bivalent data with the energetic parameters allowed to vary.
- $N_{c,max}$ is the maximum number of connections allowed to bind simultaneously.
- The calculated H_S and S_S agree well with typical AA/TT stacking free energies [3-5].

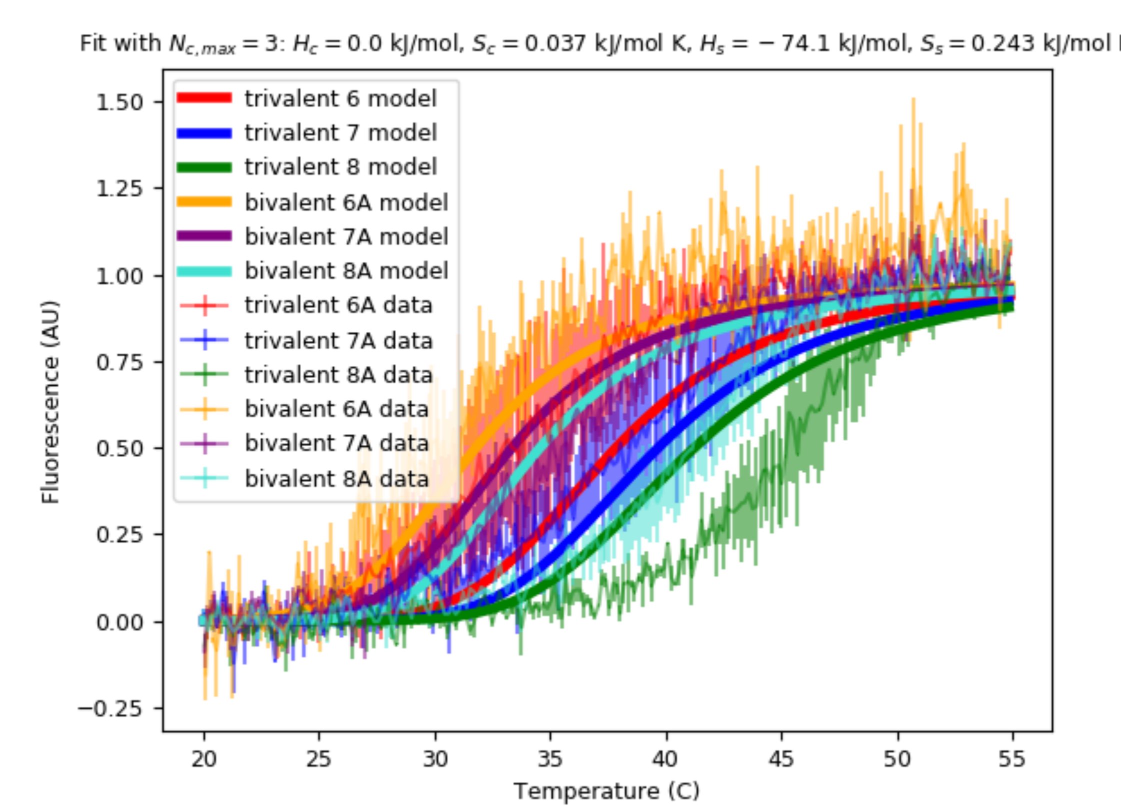
Model prediction

- Using these energetic fit parameters, a prediction is generated for mixed data
  - "mixed 6A/8A": two of the overhangs have 6/8 bases and the other has 8/6
- Next column: prediction agrees well with mixed data



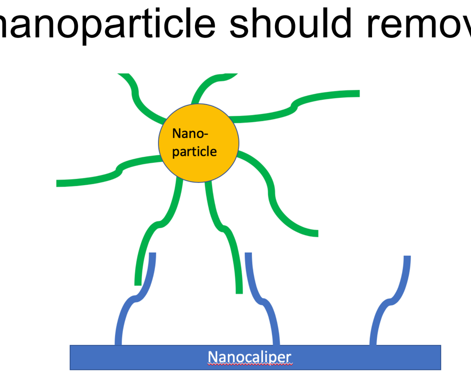
Deduction of microscopic properties

- Primary microscopic insight: only 2 overhangs are able to bind simultaneously.
  - Below: the model does not fit the data in the case that $N_{c,max} = 3$.



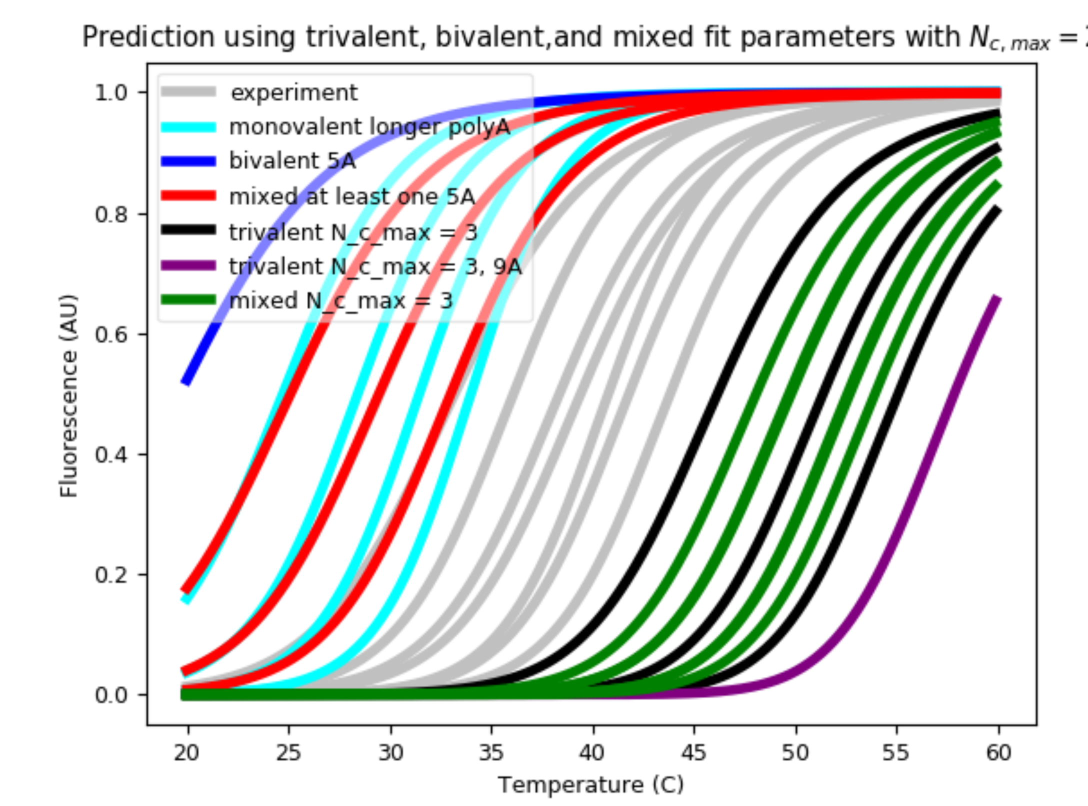
$N_{c,max}$ limit hypothesis

- The size of the nanoparticle may impose the constraint on the number of allowed simultaneous connections.
  - To test: use of a larger nanoparticle should remove this constraint.
- Nanoparticle diameter is about 5 nm
- Overhangs are oriented in a triangle with side distances of 4-5 nm



Model-directed design

- Variation of experimental parameters in the model suggests designs optimized to a given temperature.
- Below: the model can be used to choose parameters appropriate for any desired actuation temperature (within a few degrees) from 20°C to 60°C.



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