Model-Potential-Free Determination of the Interaction Potential between Biological Sensing Nanoparticles

We have devised a novel approach for determining the interaction potential between nanoparticles without needing to use specific model functions. The effect of particle–particle interference in the mesoscopic region obtained from small-angle X-ray scattering was coupled with a model-potential-free liquid theory that is fully adapted for nanoparticles with strong van der Waals attraction. The present method extracts the excess interaction potential between nanoparticles even in systems with complicated interactions of soft matter, such as polymers and biomolecules. Using this method, an interaction potential surface between biological sensing nanoparticles was realized for the first time.

Nanoparticles constitute key materials in the fields of nanoscience and nanotechnology. Biological sensing utilizing colloidal nanoparticles has been spreading to a diverse range of fields since Mirkin *et al.* reported their use in DNA biological nanosensing [1]. The sensing technology is controlled by the assembly/disassembly of nanoparticles dominated by interaction forces between them. Although the interaction potential surface provides decisive information regarding the core mechanism of the nanosensing, it has been impossible to evaluate the quantitative profile because of the extremely complicated interactions of conjugated soft matter.

In the mid twentieth century, B. Derjaguin, L. Landau, E. J. W. Verwey and J. T. G. Overbeek devised a characterization theory for the interaction potential between colloid particles during the same period [2, 3]. Their colloid stabilization theory is based on the sum of screened Coulomb repulsions and London–van der Waals attractions. The DLVO (Derjaguin–Landau–Verwey–Overbeek) model is a well-known and essential theory for understanding the interactions in colloidal systems with electrostatic interactions. To consider other interactions, the attractive interactions in the original DLVO model are often replaced by a Yukawa-type potential with variable parameters. Additional terms are also applied to the total potential surface, V_T^{DLVO}, in the DLVO model as follows: $V_T^{DLVO} = V_R^{el} + V_A^{vdw} + V'$, where V_R^{el} is the electrostatic repulsion force, V_A^{vdw} is the van der Waals attraction force, and V' is for other additional term(s). Studies on potential surfaces using the DLVO theory assume specific model-potential functions according to variations in the classified soft matter effects.

However, the assumptions underlying these specific model-potential functions lead to a limited understanding of the variety of particle–particle interactions conjugated with various types of soft matter. In fact, evaluation of a quantitative profile of the interaction potential between biological sensing nanoparticles, even by using the refined DLVO-type theory, has been impossible due to the presence of too many non-classified effects and the corresponding unknown parameters from the conjugated soft matter. Recently, Sumi and our research group devised a new approach to extract the potential energy surface for biomolecules, such as proteins, without needing to use specific model-potential functions [4]. By fully adapting this methodology to nanoparticles in the calculations and the experimental procedures, the interaction parameters between nanoparticles conjugated with soft matter can be assessed without assuming any model-potential functions [5]. In this method, an experimental structure factor evaluated from small-angle X-ray scattering (SAXS) measurement—the wide-angle-scattering data is missed—is used as an input for solving the special integral equation shown in Fig. 1, and then the interaction potential and radial distribution function as well as an all q-range structure factor can be extracted.

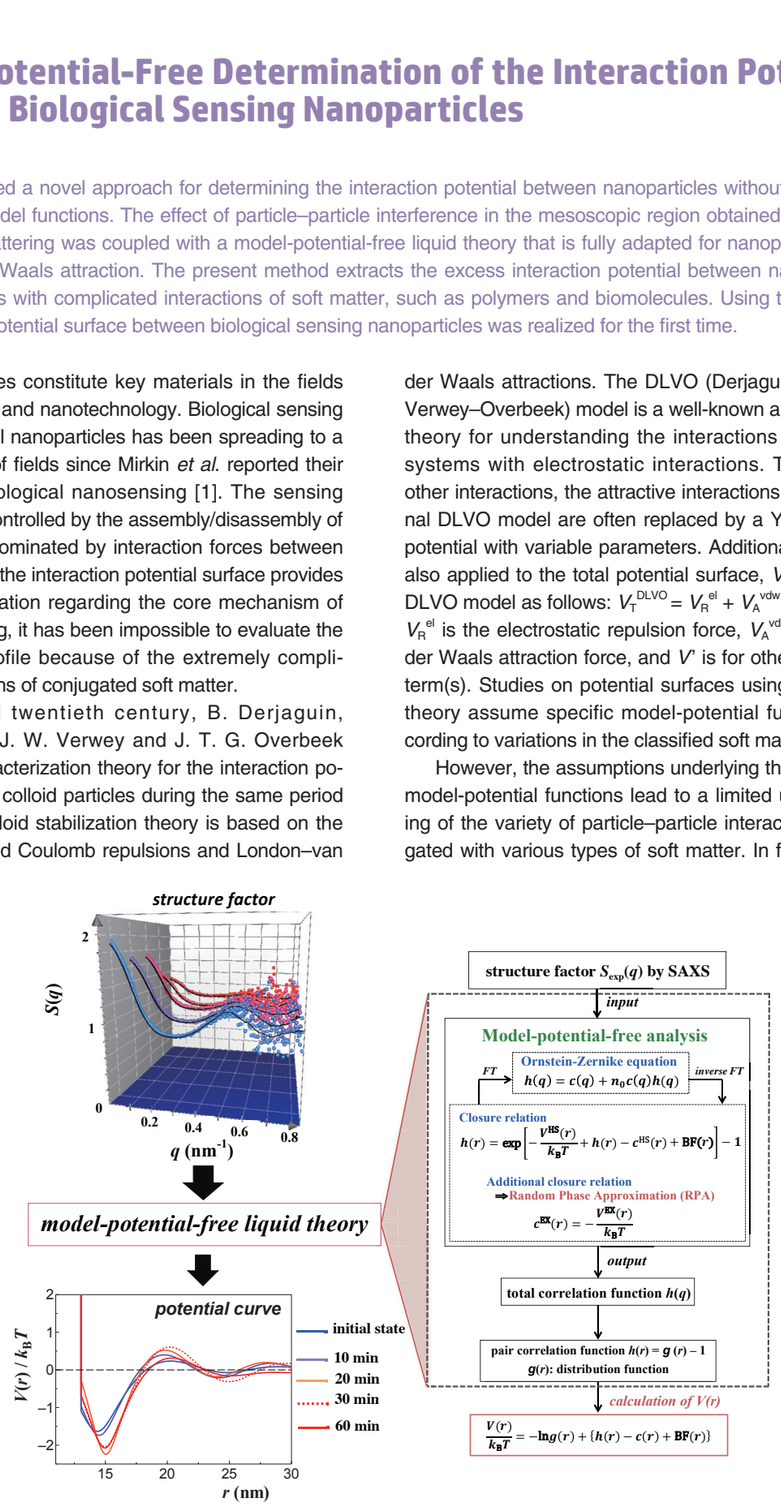

Figure 1: Structure factor $S(q)$ during the biological nanosensing reaction (at initial state, 10, 20, 30, and 60 min after the reaction started, from the near side to the far side of the figure) and the evaluated interaction potential curves. The right-hand side diagram shows a summary of the present model-potential-free analysis.

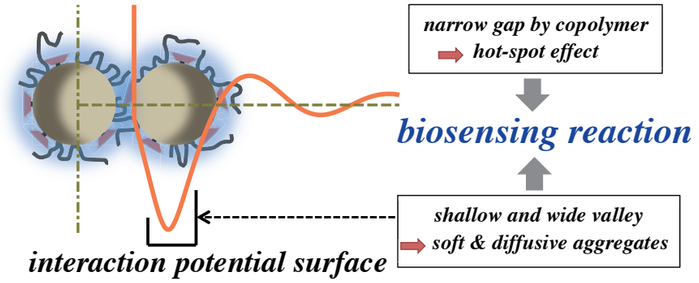

Figure 2: Schematic representation of the pairing structure and specific features of the biological sensing nanoparticles revealed by the interaction potential surface.

A biosensing reaction based on a functionalized polymer developed by Uehara and coworkers [6] was performed with a thiol derivative of glutathione and polymer-conjugated gold nanoparticles. Time-resolved SAXS measurements were carried out during the sensing reaction at the SAXS beam lines of the Photon Factory using an *in situ* titanium sample holder developed for simultaneous measurements of SAXS and UV–vis spectra [7]. The structure factor, $S(q)$, the particle–particle spatial structure between the nanoparticles, was resolved from SAXS signals based on the information on shape factor of the nanoparticles used in the experiment. The obtained $S(q)$ was used as input data for the model-potential-free determination. Figure 1 shows the $S(q)$, evaluated potential surfaces and procedure of the model-potential-free method.

As shown in Fig. 2, a profile that is shallow in depth and wide in width was observed in the primary minimum of the potential curve. This gradual change gives decisive information with respect to interactions between biological sensing nanoparticles. The potential surface leads to the flexible assembly/disassembly behavior of the nanoparticles. The narrow gap between the particle surfaces is evidence of the colorimetric sensing function based on the hot-spot band by the near-field effects between the nanoparticle surfaces, by which we can observe the change in color of the sensing solution.

The present method is applicable to investigations on the interaction potential in nanoparticles conjugated with various types of soft matter. Further investigations should be performed using the present approach to allow deeper insight into the basic stabilization of nanoparticles conjugated with soft matter, as well as assembly/disassembly during the nanosensing reaction. The present theory will contribute to revealing not only the mechanism of the sensing technology but also to an understanding of the features of complicated colloid systems with respect to interaction forces.

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BEAMLINES

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