PRF # 57801-ND9

Project Title: In Situ Small Angle Scattering Analysis of Ultrasound Excitation of Emulsion Droplets

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Research Objectives and Milestones:

Objective 1: Design of an ultrasound sample environment for SANS and SAXS analysis

With aid from PRF funding we were able to develop a new sample environment that enabled the *in-situ* analysis of colloidal and polymer systems via small angle x-ray or neutron scattering (SAXS or SANS) during ultrasonic actuation with control over pulse frequency, duty-cycle, intensity, frequency and numerous other parameters.[1] **Figure 1a** shows the key components of the ultrasound sample environment, which include a high-intensity focused ultrasound transducer, a sample cell with orthogonal acoustic and x-ray/neutron beam delivery paths and a PVDF transducer to acoustically detect cavitation events. This sample environment, which is unique in the world, helped us to complete several research projects focused on sono-crystallization of conjugated polymers, acoustics-driven formation of Pickering emulsions (Obj 2) and the analysis of mass transport in emulsion systems during ultrasound insonation (Obj. 3). This instrument was also highlighted in the NIST Center for Neutron Research Annual Report for 2018.

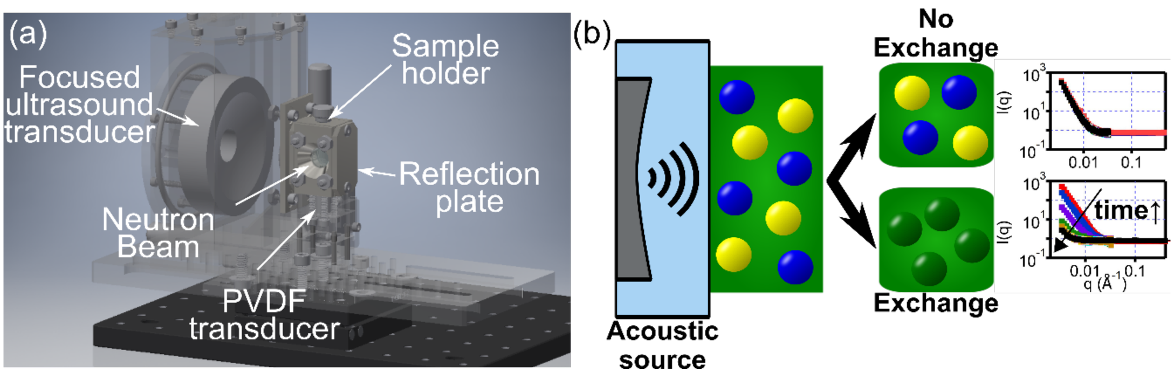

Figure 1. (a) In-situ ultrasound sample environment for small angle neutron scattering experiments. (b) Schematic diagram of ultrasound induced oil exchange where oil molecules exchanging between droplets would result in a decrease in the detected scattering intensity.

Objective 2: Probe effects of ultrasound fields on emulsion structure and interactions

In this project objective, we used the above ultrasonic sample environment (Obj. 1) to analyze the effects of acoustic cavitation on the formation of particle-stabilized (Pickering) emulsions. A model system of gold nanoparticles functionalized with amphiphilic surface coatings was used to explore the role of cavitation on the formation and structural manipulation of Pickering emulsions. It was determined that spontaneous adsorption of nanoparticles was negligible in the absence of acoustic cavitation due to significant repulsive barriers that prevented particles from approaching the oil-water interface with sufficient force to permanently attach to the surface. Synchrotron ultra small angle x-ray scattering (USAXS) was used along with the ultrasound sample environment to probe and quantify particle adsorption in-situ during ultrasound actuation.[2] A geometric model for Pickering emulsions was used to quantify the number of free particles in dispersion as well as the amount of emulsion surface area that was covered by adsorbed particles.

Objective 3: Time-resolved scattering analysis of mass transport in emulsion systems under ultrasound:

In the third objective, we used the ultrasound sample environment for the analysis of oil transport (i.e. oil mixing) in oil-in-water emulsions as a result of ultrasound insonation. This is, to the best of our knowledge, the first time that this has been explored. To do this, we applied the technique of time-resolved contrast variation SANS (CV-SANS) using mixtures of identical oil-in-water emulsion samples that were prepared with variations in the isotopic composition of the oil (e.g. D-hexadecane vs H-Hexadecane). Since isotopes can have widely different neutron scattering cross-sections, it is possible to track the mixing rate of oil molecules as a function of time (**Figure 1b**). Maximum scattering intensity is observed when emulsion droplets are in the pure (unmixed) state. As the droplets exchange oil molecules, the isotopic composition of the oil tends towards an average value that is intermediate between the two pure oils. At this condition, the emulsion droplets are designed to have zero net contrast with the surrounding fluid (water) and scattering should be minimal. It was again determined that cavitation was essential to inducing oil transport via coalescence and breakup of droplets. Moreover, it was also determined that the addition of anionic surfactants at variable concentrations would have a non-linear effect on the kinetics of oil exchange. This was rationalized by the impact of surfactant molecules on the stability of the interface due to increases in surface charge and in interfacial elasticity. In addition to probing oil exchange rates occurring during sonication, the CV-SANS technique was also utilized to analyze emulsions at rest (no external field) to attain a baseline analysis of diffusive transport occurring in emulsions. From these experiments, it was determined that the solubility of the oil in the continuous phase, the temperature of the sample and the type of surfactant (anionic vs non-ionic) were primary factors in the determination of exchange kinetics at rest. Moreover, for anionic surfactants, the exchange process would take several hours for long-chain alkanes (e.g. hexadecane), while it would occur over a few minutes when ultrasound-induced cavitation was present. At the time of writing, these results are undergoing peer-review for publication in two separate manuscripts. These results were also an integral part of the PhD thesis of one graduate student (Lee).

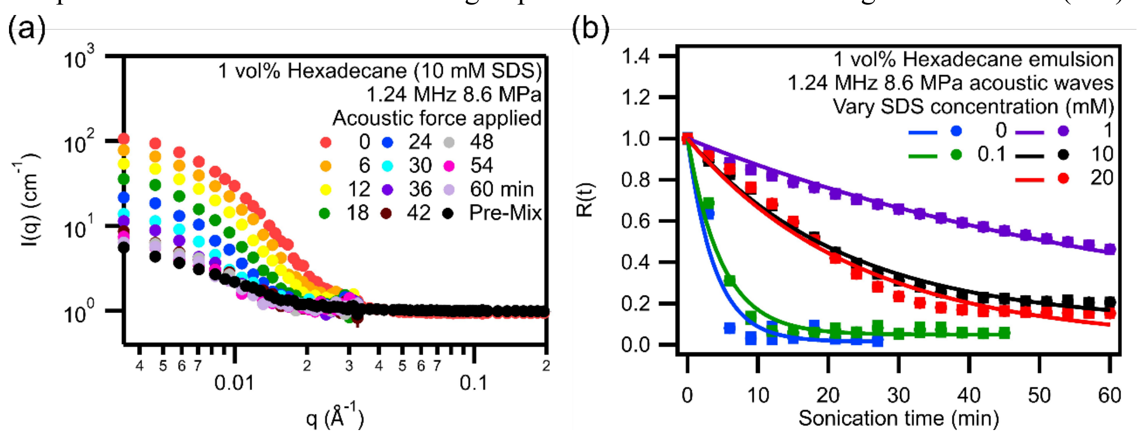

Figure 2. (a) CV-SANS profiles of ultrasound induced oil exchange between hexadecane droplets stabilized by 10 mM SDS. (b) Relaxation decay curves with modeled fits (Eq 2) for emulsion systems containing various concentration of SDS and sonicated using the in-situ ultrasound environment.

Impacts on education and career development: The project was run primarily by graduate student Yi-Ting Lee who completed his PhD thesis in Chemical Engineering thanks to the support of the PRF. As part of this thesis work, the student learned about acoustic physics, colloidal systems and scattering analysis. The student was also able to publish in leading journals, present talks at national meetings and is first author of three manuscripts that were submitted for peer-reviewed publication during the duration of the grant.

In addition to this, the grant has enabled me (the PI) to explore new research directions in the field of colloidal systems under acoustic fields and on the use of time-resolved neutron scattering to analyze transport. I am now able to apply my expertise in colloid and scattering sciences to other important applications involving ultrasound. The project has catalyzed numerous new directions ranging from fundamental analyses of emulsion transport to taste-masking of emulsified drugs for pediatric delivery.

References.

1. Li, D. S.; Lee, Y. T.; Xi, Y. Y.; Pelivanov, I.; O'Donnell, M.; Pozzo, L. D., A small-angle scattering environment for in situ ultrasound studies. *Soft Matter* **2018,** *14* (25), 5283-5293.
2. Lee, Y. T.; Li, D. S.; Ilaysky, J.; Kuzmenko, I.; Jeng, G. S.; O'Donnell, M.; Pozzo, L. D., Ultrasound-based formation of nano-Pickering emulsions investigated via in-situ SAXS. *Journal of Colloid and Interface Science* **2019,** *536*, 281-290.