Proton hyperpolarization relay from nanocrystals to liquid water†

N. Matsumoto,[*1] K. Nishimura,[*1] N. Kimizuka,[*1] Y. Nishiyama,[*2] K. Tateishi,[*3,*4] T. Uesaka,[*3,*4] and N. Yanai[*1,*4,*5]

While nuclear magnetic resonance (NMR) spectroscopy is indispensable over a wide range of fields from chemistry to medicine, it suffers from inherently poor sensitivity due to low nuclear spin polarization. Dynamic nuclear polarization (DNP), in which the electron spin polarization is transferred to the nuclear spins, is one of the most promising methods to improve the sensitivity of NMR. Water is an extremely attractive and ubiquitous target material because hyperpolarized water can lead to highly sensitive NMR of proteins and biomolecules.[1] Here, we report the nuclear spin hyperpolarization of bulk liquid water achieved via a novel strategy called "hyperpolarization relay," in which the photogenerated transient electron spin polarization is transferred to the nuclear spins within nanocrystals, and then transferred to the nuclear spins of liquid water (Fig. 1).

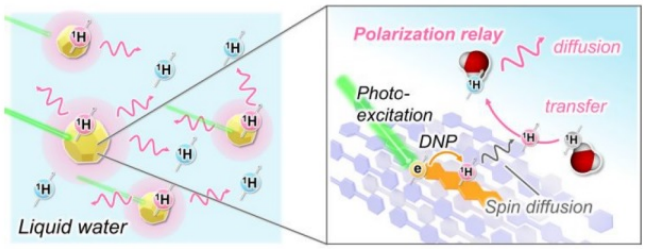

Fig. 1. Schematic of "hyperpolarization relay" from nanocrystals to bulk liquid water.

We prepared organic nanocrystals of 5,12-diazatetracene (DAT)-doped *p*-terphenyl (Fig. 2(a))[2] using the reprecipitation method,[3] that can be hyperpolarized at room temperature by DNP based on photoexcited triplet state (triplet-DNP).[4] The size of nanocrystals was characterized by dynamic light scattering (DLS) measurements. Nanocrystals of three sizes were fabricated and referred to as NC_{390}, NC_{270}, and NC_{170}, respectively. The number represents the average diameter of the nanocrystal. The nanocrystals were mixed with water of 10% H_2O in D_2O with a weight ratio of NC: water = 1 : 4 for the triplet-DNP experiments.

In the ^{1}H NMR spectrum for the mixture of NC_{170} and water at thermal equilibrium, only a sharp peak from water was observed (Figs. 2(b) and 2(c)). After a triplet-DNP sequence for 120 s, the intensity of the water-derived sharp peak clearly increased in addition to the enhanced nanocrystal-derived broad peak. The

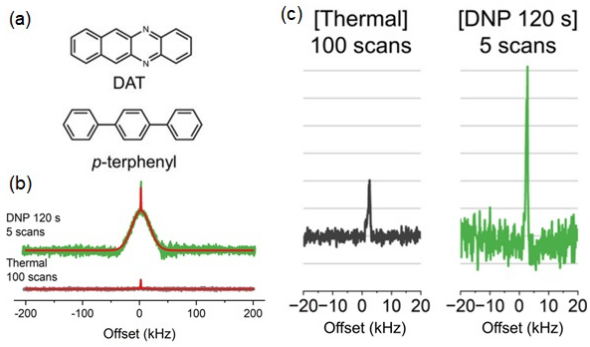

Fig. 2. (a) Chemical structures of DAT (5,12-diazatetracene) and *p*-terphenyl. (b) ^{1}H NMR spectra of the mixture of NC_{170} and water at thermal equilibrium (black) and after triplet-DNP for 120 s (green). (c) Enlarged ^{1}H NMR spectra before (black) and after triplet-DNP for 120 s (green) after subtracting the fitted spectra of NC_{170}.

enhancement factor of nanocrystals and water was estimated as 104 ± 10 and 2.4 ± 0.3 times, respectively. The transfer of proton spin polarization from the nanocrystal surface to water was indicated by the size dependence of the nanocrystals. As the nanocrystal size increased from 170 nm to 270 nm and 390 nm, the enhancement of water polarization decreased from 2.4 ± 0.3 to 1.5 ± 0.2 and 1.2 ± 0.1 times. This trend supports that the polarization transfer occurs at the interface between the nanocrystals and water.

To better understand the nanocrystal-to-water polarization transfer mechanism, the polarization buildup was simulated using Solomon equations. Interestingly, a negative cross relaxation rate constant was obtained, which often occurs in macromolecules or viscous liquids. This implies that the water dynamics are slowed at the surface of nanocrystals. A possible scenario is that polarization is transferred from the nanocrystals to the surface-bound water and that the surface-bound water exchanges with the bulk water, resulting in the enhanced polarization of the bulk water.

In conclusion, we demonstrated the polarization relay that first transfers the polarization from photoexcited triplet electron spins to proton spins within the nanocrystals, and then transfers the polarization to proton spins of water on the nanocrystal surface. This will lead to the realization of a continuous hyperpolarized water supply system that will revolutionize life science and drug discovery.

† Condensed from the article in J. Am. Chem. Soc. **144**, 18023 (2022)

*1 Department of Applied Chemistry, Kyushu University
*2 RIKEN-JEOL Collaboration Center, RIKEN
*3 RIKEN Nishina Center
*4 Spin-Isospin Laboratory, CPR, RIKEN
*5 PRESTO and FOREST, JST

References

1) T. Harris *et al.*, J. Phys. Chem. B **118**, 3281 (2014).
2) H. Kouno *et al.*, J. Phys. Chem. Lett. **10**, 2208 (2019).
3) H. R. Chung *et al.*, J. Cryst. Growth **294**, 459 (2006).
4) K. Nishimura *et al.*, Chem. Commun. **56**, 7217 (2020).