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Dynamic Nuclear Polarization with Photoexcited Triplet Electrons in a Glassy Matrix**

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NMR spectroscopy and MRI are powerful methods for the non-destructive analysis of microscopic structures inside bulk materials and human bodies. As a method to enhance their sensitivities, dynamic nuclear polarization (DNP) has attracted great attention. The intensity of a signal from nuclear spins is proportional to the spin polarization. In magnetic fields conventionally used for NMR spectroscopy and MRI, thermal polarization of nuclear spins at room temperature is in the order of 10^{-5} or less. DNP is a means of transferring spin polarization from electrons to nuclei.[1] The thermal polarization of electron spins is 660 times larger than that of ^{1}H spins, and therefore, DNP can enhance the ^{1}H spin polarization (hence the sensitivity) by a factor of at most 660.

With a lower temperature, electron spins are more highly polarized in thermal equilibrium and therefore a higher nuclear spin polarization can be achieved with DNP. (Note that, even at lower temperature, the upper limit of the polarization enhancement factor with DNP, which is defined as the ratio of the polarization after/before DNP at the same temperature herein, is not increased.) For example, at 4.2 K in 2.5 T, the bulk nuclear polarization can reach the order of 10%. Developing special peripheral equipment, such as a sample transfer system,[2,3] a temperature jump system,[2–4] and a cryogenic magic angle spinning system,[5,6] we are able to combine hyperpolarization at cryogenic temperatures around liquid helium temperature with high-resolution NMR spectroscopy or MRI. Until now, DNP has succeeded in hyperpolarizing various materials, such as trans-membrane proteins,[7] nanocrystals of amyloid,[8] and interfaces of porous media,[9] as well as injectable molecules for MRI.[3] The sample preparation method using a glassy matrix is one of the most important factors with regards to the versatility of DNP.[5] In the above-mentioned study,[2–9] materials of interest are codoped into a glassy matrix together with free radicals.

If hyperpolarization can be achieved above liquid nitrogen temperature, the peripheral equipment and the experiments will be simplified and the application field will be broadened. There are many samples of interest for which a higher temperature is preferable. One solution for overcoming the upper limit (660) of the polarization enhancement factor achieved by conventional DNP is to use non-equilibrated electron spins as polarizing agents. A number of molecules, such as pentacene, have photoexcited triplet states where the population distribution over the triplet spin sublevels is highly biased owing to intersystem crossing regardless of temperature and magnetic field strength.[10] With single crystal samples doped with pentacene, DNP utilizing the photoexcited triplet electrons as polarizing agents[11–13] has achieved bulk ^{1}H spin polarizations of 70% at 105 K[14] and 34% at room temperature.[15] Herein, we report the first demonstration of DNP using photoexcited triplet electrons in a glassy matrix. We have succeeded in polarizing codopants in a glassy matrix doped with pentacene, as a first step to increase the variety of samples and to broaden the application field.

In the present work, we use two kinds of host molecule. One is a polar molecule, benzophenone (henceforth referred to as BZP). Another is a non-polar molecule, *o*-terphenyl (henceforth referred to as OTP). OTP glass has also been used in conventional DNP.[16] The glass transition temperatures T_g and the melting points T_m of these molecules are summarized in Figure 1, alongside mixtures of glycerol/water and ethanol/water, which are often used in conventional DNP. In the present hosts, we can perform DNP at higher temperatures than in the conventional hosts.

DNP was conducted in 0.4 T. The experimental sequence begins with laser pulse irradiation that excites the pentacene dopant in the glassy matrix. The wavelength of the laser was

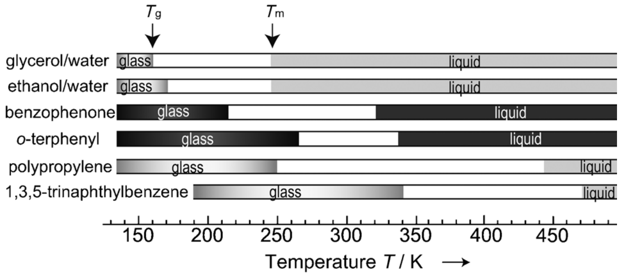

Figure 1. Glass transition temperatures T_g and melting points T_m of host materials: glycerol/water,[17] ethanol/water,[18] benzophenone,[19] *o*-terphenyl,[20] polypropylene (typical), and 1,3,5-trinaphthylbenzene.[21]

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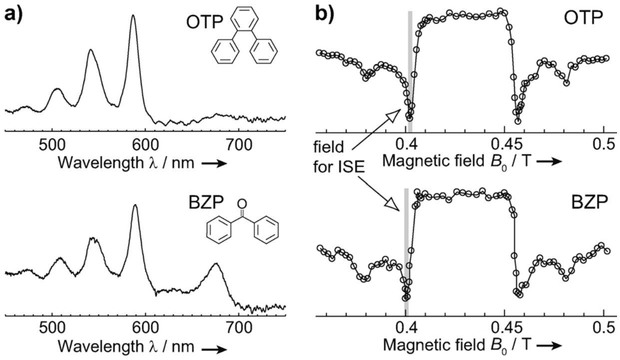

Figure 2. a) Absorption spectra of pentacene in OTP and BZP glass matrices. b) ESR spectra of pentacene in OTP and BZP glass. The magnetic fields used for the ISE are shown.

chosen to be 592 nm, which corresponds to the highest peak of the absorption spectrum of pentacene in the glassy matrix (Figure 2 a). The hyperpolarization in the photoexcited triplet state is transferred to the ^{1}H spins in the vicinity through pulse DNP, the integrated solid effect (ISE).[11] In the ISE, a field sweep and microwave irradiation near the transition frequency between the triplet sublevels are simultaneously applied in such a way that the inhomogeneously-broadened electron spin packets are adiabatically swept over and the hyperpolarization is transferred. As shown in Figure 2 b, the ESR spectra of pentacene in the glassy matrices are much broader than those in single crystals due to the ZFS (zero-field splitting) anisotropy, and resemble that in a powder sample of naphthalene doped with pentacene.[13] Takeda et al. have already shown that powder samples of naphthalene doped with pentacene can be hyperpolarized using the ISE sequence with a broader and longer field sweep than single-crystal samples.[13,22] After the photo-excited triplet state decays, the hyperpolarized state diffuses from the nuclear spins in the vicinity of the pentacene to the rest of the sample. By repeating this sequence, we can increase the nuclear spin polarization until the buildup and the nuclear spin-lattice relaxation reach equilibrium.

Supposing that hyperpolarization transferred by ISE diffuses to the whole sample in the interval of the DNP sequence (fast diffusion case), the ^{1}H spin polarization $P(t)$ is given by Equation (1):[13]

$$P(t) = \frac{P_e}{1 + T_B/T_1}\left(1 - \exp\left[-\left(\frac{1}{T_1} + \frac{1}{T_B}\right)t\right]\right) \qquad (1)$$

where P_e is the electron spin polarization just before being transferred and T_1 is the ^{1}H spin lattice relaxation time. T_B is inversely proportional to the initial gradient of the polarization buildup curve, $\mathrm{d}P(t)/\mathrm{d}t\,|_{t=0}$, and is given by $T_B = \rho_H/R\xi$, where R is the repetition rate, ξ is the polarization transfer efficiency, and ρ_H is the number of ^{1}H spins in the sample divided by the number of electron spins that participate in the polarization transfer process.

We show the thermal and polarized ^{1}H NMR spectra of OTP glass in Figure 3 a and the polarization buildup curves for the ^{1}H spins in the glassy hosts of OTP and BZP in Figure 3 b c. In OTP glass at 120 K, the final polarization attained was 0.28 %, which was 820 times larger than the ^{1}H spin polarization in thermal equilibrium at 0.40 T and 120 K. The polarization enhancement factor of 820 is larger than the upper limit of conventional DNP (660) using electron spins in thermal equilibrium. The final polarizations attained in BZP glass at 120 K was 0.06 %.

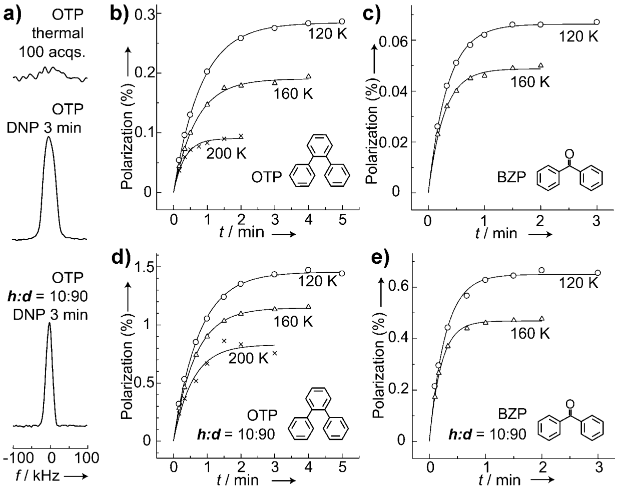

Figure 3. a) ^{1}H NMR spectra of thermal and polarized OTP glass matrices and ^{1}H spin polarization buildup curves for b) OTP, c) BZP, d) partially deuterated OTP ([D$_{14}$]OTP/OTP = 90:10 wt %), and e) partially deuterated BZP ([D$_{10}$]BZP/BZP = 90:10 wt %) doped with 0.05 mol % pentacene at 120 K (○), 160 K (△), and 200 K (×).

The polarizations achieved were much smaller than the electron spin polarization P_e, which was in the order of 10 % averaged over the ISE duration, meaning T_B/T_1 in Equation (1) must be larger than 10. The decrease in T_B/T_1 increases the achievable polarization. To decrease T_B, we decreased ρ_H by deuteration.[13,23,24] The results with 90 wt % deuterated hosts are shown in Figure 3 d,e. In partially deuterated OTP glass at 120 K, the achieved polarization was 1.45 % (the ^{1}H NMR spectra is shown in Figure 3 a), which gives a polarization enhancement factor of 4250. All of the polarizations achieved in OTP and BZP glass matrices were increased by a factor of more than five by deuteration.

We have succeeded in obtaining enhanced signals from ^{19}F spins of molecules codoped with pentacene in glass at 120 K. 1 mol % 2,3,4-trifluorobenzoic acid was doped into [D$_{14}$]OTP/OTP = 90:10 wt % with 0.05 mol % pentacene. The ^{1}H spin polarization attained was 0.8 %. In the codoped sample, T_1 becomes shorter and the attainable polarization of ^{1}H spins becomes about half that of a sample without the codopants. A polarized ^{19}F NMR spectrum of 2,3,4-trifluorobenzoic acid is shown in Figure 4 a. Polarization transfer from ^{1}H to ^{19}F spins was realized with field cycling instrumentation (0.4 T → 0.01 T → 0.4 T).[25] In 0.01 T, the resonance frequency difference between the ^{1}H and the ^{19}F spins is the same order as the strength of the nearest neighbor ^{1}H–^{19}F dipolar coupling, so polarization transfer occurs. The efficiency of the polarization transfer between ^{1}H and ^{19}F spins was estimated to be about 70 %, which was degraded by the spin lattice relaxation in the very low magnetic fields. We also show a ^{19}F NMR spectrum

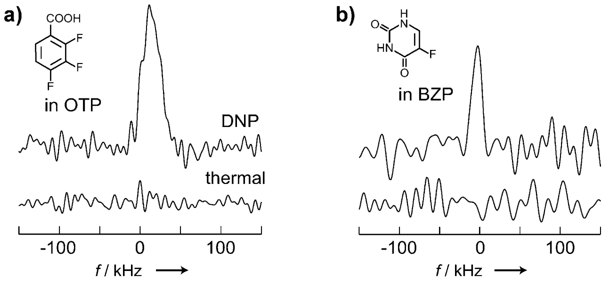

Figure 4. Polarized ^{19}F NMR spectra of a) 2,3,4-trifluorobenzoic acid and b) 5-fluorouracil in glassy matrices. After DNP for 3 min and field cycling, the ^{19}F NMR signals were acquired. The NMR signals of the samples in 0.40 T at 120 K in thermal equilibrium are also shown.

of 1 mol% 5-fluorouracil codoped into [D_{10}]BZP/BZP = 90:10 wt% with 0.05 mol% pentacene in Figure 4b.

In this work, we have achieved bulk polarization of 1.45% in a glassy matrix with DNP using photoexcited triplet electrons. The achieved polarization enhancement factors in glassy matrices are larger than 660, the upper limit of the polarization enhancement factor with conventional DNP using thermal electrons. Herein we discuss the potential to achieve a higher polarization. Equation (1) implies that a higher polarization can be obtained by increasing one or some of the following parameters: 1) The deuteration factor for lower ρ_H (note that the optimum value exists due to the decrease of the spin diffusion constant[24]); 2) the concentration of polarizing agents for lower ρ_H; 3) R using a different laser source,[26] 4) T_1; 5) ξ; and 6) P_e. There are some molecules in which the photoexcited triplet state has a higher P_e.[10] Although spin lattice relaxation can be suppressed by regioselective deuteration of the host materials as well as full deuteration of pentacene (4),[15] other host molecules with a longer T_1 should be researched and developed. Experimental time was in the order of minutes to polarize, while the conventional DNP requires the time in the order of 10 seconds or less. By increasing (2) and (3), we can reduce the polarization buildup time.

Glassy matrices can be used to dissolve and hyperpolarize various molecules; therefore, they have been also used for conventional DNP using thermal electrons.[2–9] In this work, we have also succeeded in hyperpolarizing ^{19}F spins of molecules codoped with pentacene in glassy matrices. The enhanced solid-state ^{19}F NMR spectra were not highly resolved because of the low field and the absence of dipolar decoupling techniques such as magic angle spinning (MAS). According to the history of conventional DNP, there are two ways toward high-resolution NMR spectroscopy. One is carrying out DNP in a strong magnet conventionally used for high-resolution NMR with higher-frequency instrumentation.[5] For ISE, the electron nutation frequency should be matched with the nuclear Larmor frequency.[11] Therefore, the microwave field strength required for ISE is proportional to the static field strength, which poses a limiting factor for this approach. The other way is simpler and utilizes a field-cycling system to move from a magnet for DNP to another magnet for high-resolution NMR.[2] We have already developed the field cycling instrumentation with a triple-resonance (^{1}H–^{13}C–^{2}H) NMR probe in a strong, homogeneous superconducting magnet of 11.7 T and a magnet of 0.4 T for DNP using photoexcited triplet electrons.[27] Additional systems, such as a temperature-jump system,[2–4] a system for sample injection to MAS probe,[28] and MAS rotor with transparent material[29] have already been developed or commercialized for other purposes and can be more easily combined with DNP using photoexcited triplet electrons because the present DNP is carried out at higher temperatures. This will make DNP using photoexcited triplet electrons a more feasible method for boosting the sensitivity of high-resolution liquid/solid-state NMR spectroscopy or MRI. The samples for which a higher temperature is preferable are in the scope of the present method.

Applications to a wider research field require contributions from organic chemists to search for more suitable glassy hosts as well as other triplet polarizing agent. One of the most important steps in the future is the demonstration of DNP in bulk material using triplet polarizing agents other than pentacene. For example, one of fullerene-derivatives, dimethyl[9-hydro(C_{60}-I_h)[5,6]fullerene-1(9*H*)-yl]phosphonate,[30] has succeeded in polarization transfer from photoexcited triplet electrons to nuclei, albeit inside the molecule.[31] Furthermore, some fullerene derivatives are soluble in typical organic solvents and water. For MRI use, water-solubility is important, and some efforts have been made to remove polarizing agents with harmful unpaired electrons in the conventional DNP.[32] Study on human-body-friendly triplet molecules is important, because triplet polarizing agents have no unpaired electrons whereas pentacene is harmful.

Using photoexcited triplet electrons is promising to push the limitation of DNP to higher temperatures. Recently, using a single-crystal sample, we have achieved a polarization of 34% at room temperature.[15] It would be desirable to develop a glassy host with a higher glass transition temperature T_g (e.g. 1,3,5-trinaphthylbenzene, shown in Figure 1). DNP using photoexcited triplet electrons has the potential to enhance the NMR/MRI sensitivity significantly while keeping the sample at room temperature.

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