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High-field NMR with dissolution triplet-DNP

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ABSTRACT

Dissolution dynamic nuclear polarization (DNP) has wide variety of important applications such as real-time monitoring of chemical reactions and metabolic imaging. We construct DNP using photoexcited triplet electron spins (Triplet-DNP) apparatus combined with dissolution apparatus for solution NMR in a high magnetic field. Triplet-DNP enables us to obtain high nuclear polarization at room temperature. Solid-state samples polarized by Triplet-DNP are transferred to a superconducting magnet and dissolved by injecting aqueous solvents. The ^{13}C polarization of 0.22% has been obtained for [caryboxy-^{13}C]benzoic acid-*d* in the liquid state. Our results show that Triplet-DNP can be applied to real-time monitoring with solution NMR.

1. Introduction

NMR spectroscopy has crucial roles for non-invasive material analyses. However, the inherent low sensitivity, due to the extremely low thermal polarizations at room temperature even in a high magnetic field, limits the range of applications. Dynamic nuclear polarization (DNP) [1] provides a way to significantly enhance the nuclear spin polarizations using unpaired electron spins, which have high polarization compared to nuclear spins. The high polarization can be transferred to nuclear spins by microwave irradiation at or near the resonant frequency of electron spins. DNP instruments have opened a wide variety of new NMR/MRI applications. For example, DNP combined with magic angle spinning [2] is utilized for characterizations of tiny amount of samples (~100 nmol) such as trans-membrane proteins [3,4] and surface structures of porous materials [5] in the solid state. Dissolution DNP (d-DNP) [6] can monitor real-time chemical reactions and metabolic processes [7–10]. To obtain near unity electron polarization along with a long nuclear spin-lattice relaxation time, d-DNP experiments are generally carried out at low temperatures (<2 K) in high magnetic fields (>3 T). After the DNP experiments, the samples are rapidly dissolved by hot solvents and transferred to a secondary NMR or MRI superconducting magnet (SCM). Several instruments have been reported in the literature [11–13].

While the conventional DNP, which is implemented at low temperature in a high magnetic field using free radicals, is the most versatile method, several methods such as para hydrogen [14], nitrogen-vacancy center in diamonds [15] and optically pumped gases [16] are studied as promising candidates to obtain extremely high nuclear polarizations. As the sources of high polarization in these methods are not thermally equilibrated electron spins, these techniques do not require high magnetic fields and/or cryogenic temperatures. DNP using photoexcited triplet electron spins (Triplet-DNP) [17–19] also can be carried out under low magnetic fields and high temperatures. The triplet state of pentacene has high polarization under those experimental conditions because the population is selectively distributed via intersystem crossing [20,21]. The high polarization is transferred to nuclear spins by microwave irradiation during the lifetime of the triplet state. Using Triplet-DNP, ^{1}H polarization of above 70% in a single crystal of naphthalene was obtained below 100 K [22,23] and ^{1}H polarization of 34% was achieved in a single crystal of *p*-terphenyl at room temperature [24]. Recently, we have advanced this technique toward the application in NMR/MRI analyses. Eutectic mixtures [25] and glassy host molecules [26] have been investigated to increase the number of target molecular species to be polarized by Triplet-DNP. Yanai *et al.* have studied new polarizing agents [27] other than pentacene, which has been used for the standard agent of Triplet-DNP, and realized high ^{1}H polarization of nanocrystals

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dispersed in water [28] to widen the range of Triplet-DNP applications.

In the previous work, we succeeded in obtaining solution ^{1}H NMR spectra of benzoic acid polarized by Triplet-DNP in an electromagnet of 0.39 T [29]. The static magnetic field of 0.39 T created by an electromagnet is suitable for Triplet-DNP but not for conventional solution NMR, since it is of a quite low strength and has low homogeneity compared to that of a standard NMR SCM equipped with a shim coil. We have also constructed a magnetic field cycling system between a low magnetic field for Triplet-DNP and a high magnetic field for solid NMR [30]. Recently, Kouřil *et al.* have constructed bullet-DNP system enabling fast solid-state sample transfer by pressurized He gas and rapid dissolution of the sample at room temperature without the loss of polarized target molecules [31]. Brute-force hyperpolarization also succeeds in room temperature dissolution of thermally polarized samples [32].

In this work, we apply Triplet-DNP to solution NMR in a high magnetic field. Solid-state samples polarized by DNP are transferred into a high magnetic field and dissolved by hot aqueous solvents at room temperature. Dissolution at very low temperature needs a large amount of solvent volume (3–5 mL) to prevent sample freezing. The dissolution at room temperature enabled by Triplet-DNP circumvents the large solvent volume required in the conventional DNP, which increases the sensitivity owing to the increased concentration of target molecules in the solvent. As the electromagnet for Triplet-DNP can be placed just beneath a SCM for solution NMR, a sample transfer path of our system is shorter than that of conventional d-DNP system and the polarization loss during the transfer of the solid sample is low. The ^{13}C polarization of 0.22% has been obtained for [caryboxy-^{13}C]benzoic acid-*d* in the liquid state. Our results show that Triplet-DNP can be applied to real-time monitoring of solution NMR with high resolution.

1.1. Hardware and experiments

We modified our field-cycling instrumentation that can measure single crystal samples highly polarized by Triplet-DNP [30]. As shown in Fig. 1, an electromagnet (EM40050, Echo-Denshi) and a SCM of 11.7 T (Varian Inc.) were employed for Triplet-DNP and solution NMR experiments, respectively. Integrated Solid Effect (ISE) sequence [17] was implemented to efficiently polarize ^{1}H spins. Our Triplet-DNP apparatus placed in the electromagnet is almost similar to the previous one [30]. We placed the electromagnet just beneath the SCM. The sample transfer length is 85 cm between the position of Triplet-DNP and solution NMR experiments. Conventional d-DNP systems require transfer length of several meters. The leakage magnetic field of the SCM was c.a. 20 mT at the sample position for Triplet-DNP experiments without the electromagnet. We do not utilize a magnetic tunnel, which can suppress spin-lattice relaxation (T_1) at a near zero magnetic field [33].

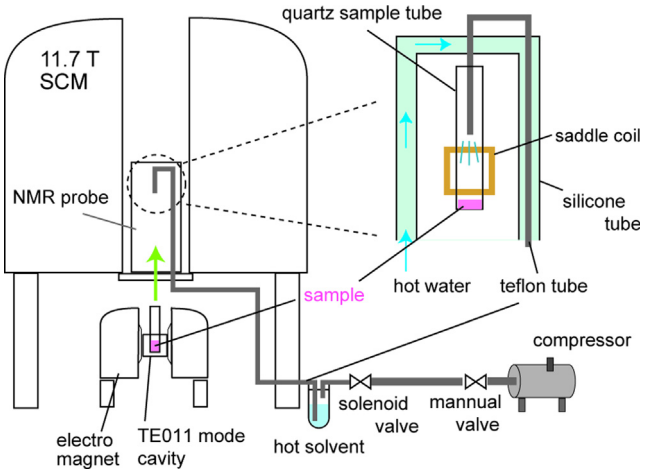

Fig. 1. Schematic diagram of our dissolution Triplet-DNP system. The electromagnet was placed just beneath the SCM.

After Triplet-DNP, solid samples were manually transferred to the 11.7 T SCM within 5 s. The fast T_1 decay brought about by the radical spins used in conventional d-DNP can be avoided in our sample transfer because there are not radical spins in the samples after Triplet-DNP experiments. Note that photo-induced radicals have the same advantage in the conventional d-DNP experiments, since the radicals recombine after dissolution [34]. We developed a ^{1}H–^{13}C double resonance probe based on the Kan's circuit design [35] and tuned at 500 and 125 MHz, respectively. Saddle shaped coil with 15 mm length and 6 mm diameter was employed as the NMR sample coil. We used a quartz sample tube with outer diameter (OD) of 5 mm and inner diameter (ID) of 3.6 mm. The sample tube is suitable for Triplet-DNP experiments using a TE_{011} mode microwave cavity with a high quality factor because of its low dielectric loss. A hot aqueous solvent for rapid dissolution was injected to the sample tube by compressed air of 0.1 MPa through a 1.5 m long Teflon tube within 1 s. To suppress the temperature drop of the solvents during the transfer, the Teflon tube was passed through a silicone tube inside which hot water circulated as shown in Fig. 1.

[*carboxy*-^{13}C]benzoic acid (BA1), [1,2,3,4,5,6-$^{13}C_6$]benzoic acid (BA6) and deuterated water (99.9% atom D) were purchased from Cambridge Isotope Laboratories. Carboxylic hydrogens in BA1 was substituted with deuterium using deuterated water to increase the ^{1}H spin–lattice relaxation times [29]. Regioselectively labelled [2,5-$^{13}C_2$]benzoic acid (BA2) was synthesized (see SI text for details of organic synthesis). The synthesized [*carboxy*-^{13}C] BA-*d* (BA1d) and BA2 were purified by sublimation. The three labelled BA molecules are shown in Fig. 2. We prepared the three sorts of ^{13}C labelled samples doped with 0.04 mol% pentacene to obtain ^{13}C NMR spectra in which J-splitting and chemical shifts are well resolved. We used the three samples milled by a pestle to easily dissolve with the hot solvents. The solvent of 0.5 M sodium hydroxide in deuterated water was used for rapid dissolution of BA.

All Triplet-DNP experiments were carried out in 0.39 T at room temperature. In 0.39 T, the resonant frequencies of electron spin, ^{1}H spin, and ^{13}C spin were c.a. 11.6 GHz, 16.6 MHz, and 4.15 MHz, respectively. Pentacene doped in BA was excited by a dye laser (RDP1, Radiant dyes). The dye laser was pumped by a green laser (DM60-527, Photonics Industries). The wavelength, energy, and pulse duration of the dye laser were 594 nm, 11 mJ/pulse, and 200 ns, respectively. The experimental parameters for the ISE sequence are shown in Fig. 3. We used a homebuilt OPENCORE NMR spectrometer [36] for the timing controls of ISE

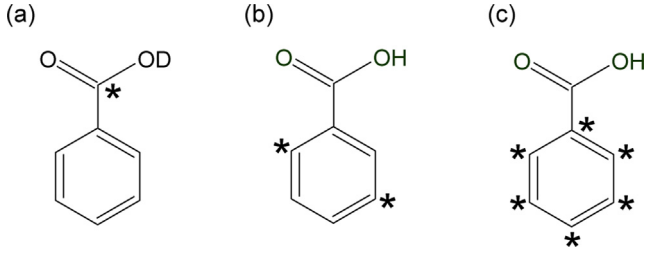

Fig. 2. Regioselectively ^{13}C-labelled benzoic acids. (a) [carboxy-^{13}C]benzoic acid-*d* (BA1d), (b) [2,5-$^{13}C_2$]benzoic acid (BA2), (c) [1,2,3,4,5,6-$^{13}C_6$]benzoic acid (BA6). Labelled ^{13}C spins are indicated by asterisks.

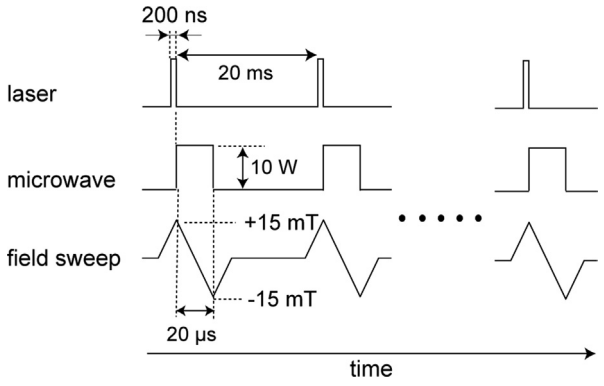

Fig. 3. ISE sequence for Triplet-DNP.

sequence and NMR measurements. After Triplet-DNP, high polarizations of ^{1}H spins were transferred to ^{13}C spins by a ramped amplitude cross polarization [37] in 0.39 T. The polarizations were estimated by comparing NMR signal intensities of highly polarized samples with those of thermally equilibrated ones in 0.39 T and 11.7 T.

2. Results and discussion

We obtained the ^{1}H polarizations of 0.37% and 0.88% for non-deuterated BA and partially deuterated BA-*d* by Triplet-DNP for 360 s in 0.39 T. The obtained polarization of deuterated BA-*d* is higher than non-deuterated BA due to the long T_1 value [29], which can be explained by the fact that the motion of carboxylic hydrogen is a main source of T_1 in the solid samples of BA. To guarantee the laser to penetrate through the whole sample, we used powder samples of c.a. 0.4 mg in a 1 mm ID pyrex tube for this experiment.

After Triplet-DNP experiments, the polarized samples of c.a. 3 mg were manually shuttled and then dissolved by the hot solvents of 0.35 mL. We obtained highly enhanced solution ^{13}C NMR spectra of BA1d, BA2, and BA6 as shown in Fig. 4. The enhancement factors were calculated by comparing the integrated intensities for the highly polarized NMR signals (S_{DNP}) and the NMR signals (S_{the}) in thermal equilibrium at room temperature in 11.7 T. The achieved enhancement factors (S_{DNP}/S_{the}) were 220, 100, and 40 for BA1d, BA2, and BA6, respectively. The corresponding ^{13}C polarizations were c.a. 0.22%, 0.10%, and 0.04%. The main reason of low ^{13}C polarization of BA6 compared to BA2 is the difference of the number of ^{13}C spins in BA. The enhancement factor of cross polarization is proportional to $\varepsilon = N(^{1}H)/(N(^{1}H) + N(^{13}C))$, where N (^{13}C) and N(^{1}H) are the number of ^{13}C spins and ^{1}H spins in BA. ε of BA2 and BA6 are 0.75 and 0.5, respectively. The relaxation times of carboxyl ^{13}C spin and ring-^{13}C spins in solutions were 48 s and less than 5 s, respectively. We also show the time dependence of the solution ^{13}C NMR spectra in Fig. 5. The first spectra just after dissolutions were broader than those of other spectra because of the inhomogeneity of the static magnetic field caused by microbubbles [38–40]. The inhomogeneity becomes stable in a few seconds after the dissolution. After the stabilization, J-splitting and chemical shifts of BA were well resolved as shown in Fig. 5. The minimum line width of BA1d in d-DNP experiments was 13 Hz, which corresponds to that in thermal state experiments with our NMR system.

We also measured solution NMR spectra of ^{1}H spins in the benzene ring of the BA1d as shown in Fig. 6. The enhancement factor was c.a. 50 and it corresponds to ^{1}H polarization of 0.2%, which was close to the obtained ^{13}C polarization. The minimum line width of 80 Hz was 2.5 times broader than that of the thermal ^{1}H spectrum. Generally, ^{1}H spins are 4 times sensitive to the homogeneity of the static magnetic field compared to ^{13}C spins due to the large gyromagnetic ratio. We measured the loss of ^{1}H polarization was only 6% during our sample transfer. Note that the T_1 of ^{1}H spins for BA-*d* in the solid state is 7 min in 0.38 T at room temperature [29]. From the result, we concluded that our sample transfer from the low field to the high field nearly fulfilled the adiabatic condition. The main source of the ^{1}H polarization difference measured at 0.39 T and 11.7 T was the difference in the sample volume; we used larger sample tubes for the dissolution experiments compared to those for the measurement of ^{1}H polarization in 0.39 T. By comparing the enhanced ^{1}H NMR signals between the sample of 0.4 mg and the sample of 3 mg, we concluded that our laser could excite approximately the half of the 3 mg sample volume. Furthermore, it takes a few second from the dissolution to stabilize the dissolved solvents. The time interval for stabilization decreases the ^{1}H polarization of BA in solution due to the short T_1 (<5 s).

A higher power laser (>20 mJ/pulse) would be required to obtain higher enhancement factors. This would enable us to excite pentacene in the whole sample volume of 3 mg, doubling the enhancement factor as mentioned above. Moreover, highly pressurized sample tubes are useful for rapid stabilization of dissolved samples [38–40]. It would enable us to measure NMR spectra just

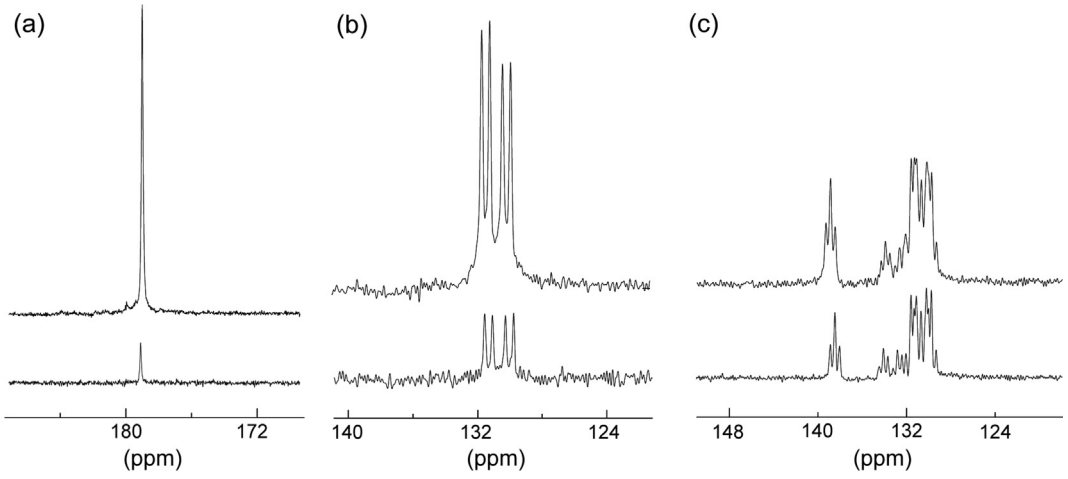

Fig. 4. Liquid ^{13}C NMR spectra in 11.7 T of (a) BA1d, (b) BA2 and (c) BA6. The bottom spectra are thermal equilibrium spectra accumulated 64 times (a, b) and 256 times (c) using a 90° pulse. The upper spectra enhanced by Triplet-DNP were acquired by a 30° pulse. The chemical shifts were calibrated using 3-(trimethylsilyl)propionic-2,2,3,3-d_4 acid, sodium salt (TSP) in D_2O.

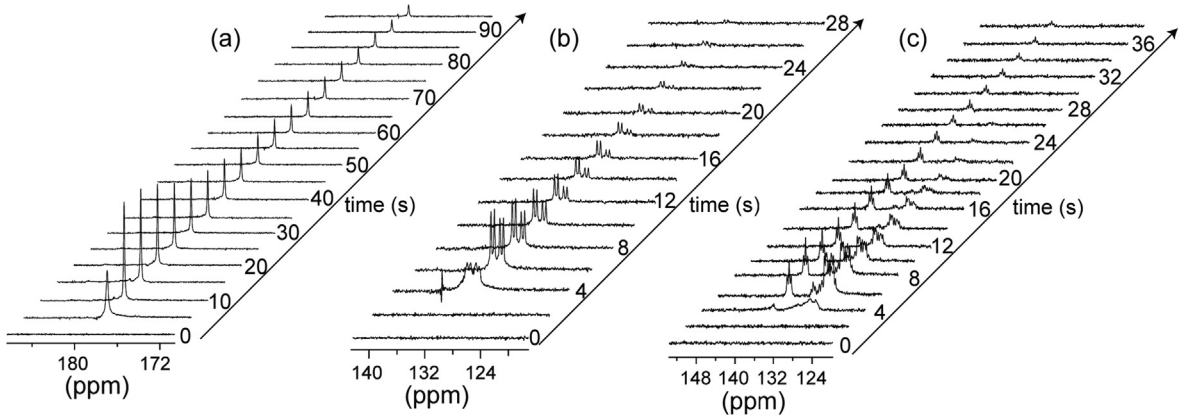

Fig. 5. Time-resolved enhanced solution ^{13}C NMR spectra. The spectra were acquired with a time interval of 5 s for (a) BA1d and 2 s for (b) BA2 and (c) BA6 using a 30° pulse. The ^{13}C NMR became visible after dissolution. The solenoid valve opens 3 s after the dissolution sequence is started and then the solvent is transferred to the polarized samples within 1 s.

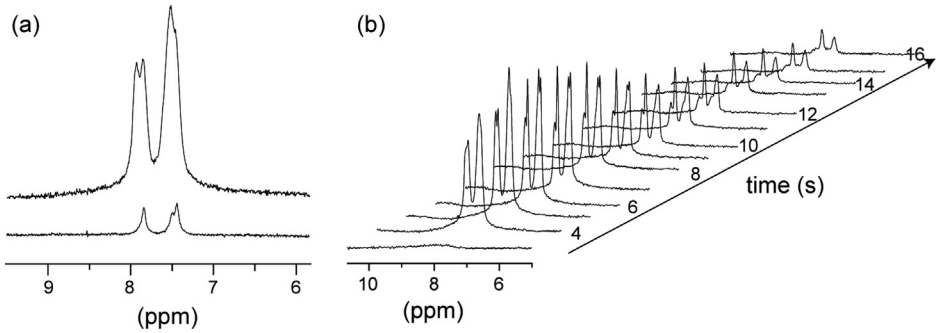

Fig. 6. Enhanced spectra of ^{1}H spins in the benzene ring of BA1d. (a) The bottom thermal spectrum was 4 times accumulated and measured by a 90° pulse. The upper enhanced spectrum was measured by a 15° pulse. (b) The spectra were acquired with a time interval of 1 s using a 15° pulse.

after the dissolution and suppress the decrease of signal intensities due to short T_1 in the liquid state. Our sample volume is smaller than that of conventional DNP method. In the case of lower pentacene concentration, we can increase the sample volume because the laser at the same power can penetrate more deeply into samples. Although the low pentacene concentrations cause a low efficiency of ^{1}H polarization build up upon DNP, a laser with a higher repetition frequency has the possibility to recover it. In fact, Eichhorn *et al.* used 0.003 mol% pentacene doped naphthalene crystal of more than 100 mg for Triplet-DNP experiments with 4 kHz laser repetition rate and achieved high nuclear polarization as mentioned above [22]. These improvements widen Triplet-DNP applications for NMR/MRI experiments in a high magnetic field. Application of Triplet-DNP apparatus introduced in this work in NMR spectroscopy such as monitoring ligand binding of benzoic acid [41] and salicylic acid [42] is currently in progress.

3. Conclusions

We have implemented dissolution Triplet-DNP in 11.7 T at room temperature. The highly enhanced ^{1}H and ^{13}C NMR signals of benzoic acid were obtained in the liquid state. The polarization loss during the transfer in the solid state was 6% for ^{1}H spins of benzoic acids in the benzene ring. The highest ^{13}C polarization obtained for carboxyl deuterated benzoic acid is 0.22% which corresponds to the enhancement factor of 220 compared to the thermal polarization. The enhancement serves real-time monitoring of solution ^{13}C NMR spectra using tip pulses. The developed instrument can be employed to NMR/MRI analyses.

Author contributions

A.K., M.N. and M.K. designed research; A.K., K.M., N.I and H.E. performed experiments; A.K., K.M analyzed data; A.K, K.M., and N.I. developed experimental instrumentation; Y.N, H.E., T.M, and Y.M synthesized regioselectively ^{13}C-labelled benzoic acid. A.K., M.N, T.M., Y.M., and M.K. wrote the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Synthesis of [2,5-$^{13}C_2$]benzoic acid is shown in SI. (PDF). Supplementary data to this article can be found online at https://doi.org/10.1016/j.jmr.2019.106623.

References

[1] A. Abragam, M. Goldman, Principles of dynamic nuclear polarization, Rep. Prog. Phys. 41 (1978) 395–467.

[2] D.A. Hall, D.C. Maus, G.J. Gerfen, S.J. Inati, L.R. Becerra, F.W. Dahlquist, R.G. Griffin, Polarization-enhanced NMR spectroscopy of biomolecules in frozen solution, Science 276 (1997) 930–932, https://doi.org/10.1126/science.276.5314.930.
[3] A.B. Barnes, G. De Paëpe, P.C.A. van der Wel, K.-N. Hu, C.-G. Joo, V.S. Bajaj, M.L. Mak-Jurkauskas, J.R. Sirigiri, J. Herzfeld, R.J. Temkin, R.G. Griffin, High-field dynamic nuclear polarization for solid and solution biological NMR, Appl. Magn. Reson. 34 (2008) 237–263, https://doi.org/10.1007/s00723-008-0129-1.
[4] Q.Z. Ni, E. Daviso, T.V. Can, E. Markhasin, S.K. Jawla, T.M. Swager, R.J. Temkin, J. Herzfeld, R.G. Griffin, High frequency dynamic nuclear polarization, Acc. Chem. Res. 46 (2013) 1933–1941, https://doi.org/10.1021/ar300348n.
[5] A.J. Rossini, A. Zagdoun, M. Lelli, A. Lesage, C. Coperet, L. Emsley, Dynamic nuclear polarization surface enhanced NMR spectroscopy, Acc. Chem. Res. 46 (2013) 1942–1951, https://doi.org/10.1021/ar300322x.
[6] J.H. Ardenkjaer-Larsen, B. Fridlund, A. Gram, G. Hansson, L. Hansson, M.H. Lerche, R. Servin, M. Thaning, K. Golman, Increase in signal-to-noise ratio of > 10,000 times in liquid-state NMR, Proc. Natl. Acad. Sci. U.S.A. 100 (2003) 10158–10163, https://doi.org/10.1073/pnas.1733835100.
[7] K.R. Keshari, D.M. Wilson, Chemistry and biochemistry of ^{13}C hyperpolarized magnetic resonance using dynamic nuclear polarization, Chem. Soc. Rev. 43 (2014) 1627–1659, https://doi.org/10.1039/C3CS60124B.
[8] K. Golman, R.I. Zandt, M. Thaning, Real-time metabolic imaging, Proc. Natl. Acad. Sci. U.S.A. 103 (2006) 11270–11275, https://doi.org/10.1073/pnas.0601319103.
[9] S.E. Day, M.I. Kettunen, F.A. Gallagher, D.E. Hu, M. Lerche, J. Wolber, K. Golman, J.H. Ardenkjaer-Larsen, K.M. Brindle, Detecting tumor response to treatment using hyperpolarized ^{13}C magnetic resonance imaging and spectroscopy, Nat. Med. 13 (2007) 1382–1387, https://doi.org/10.1038/nm1650.
[10] S.J. Nelson, J. Kurhanewicz, D.B. Vigneron, P.E.Z. Larson, A.L. Harzstark, M. Ferrone, M. Criekinge, J.W. Chang, R. Bok, I. Park, et al., Metabolic imaging of patients with prostate cancer using hyperpolarized [1-^{13}C] pyruvate, Sci. Tans. Med. 5 (2013) 198ra108, https://doi.org/10.1126/scitranslmed.3006070.
[11] F. Jähnig, G. Kwiatkowski, M. Ernst, Conceptual and instrumental progress in dissolution DNP, J. Magn. Reson. 264 (2016) 22–29, https://doi.org/10.1016/j.jmr.2015.12.024.
[12] J.H. Ardenkjaer-Larsen, On the present and future of dissolution-DNP, J. Magn. Reson. 264 (2016) 3–12, https://doi.org/10.1016/j.jmr.2016.01.015.
[13] S. Jannin, J.-N. Dumez, P. Giraudeau, D. Kurzbach, Application and methodology of dissolution dynamic nuclear polarization in physical, chemical and biological contexts, J. Magn. Reson. 305 (2019) 41–50, https://doi.org/10.1016/j.jmr.2019.06.001.
[14] S.B. Duckett, R.E. Mewis, Application of parahydrogen induced polarization techniques in NMR spectroscopy and imaging, Acc. Chem. Res. 45 (2012) 1247–1257, https://doi.org/10.1021/ar2003094.
[15] J.P. King, K. Jeong, C.C. Vassiliou, C.S. Shin, R.H. Page, C.E. Avalos, H.-J. Wang, A. Pines, Room-temperature in situ nuclear spin hyperpolarization from optically pumped nitrogen vacancy centres in diamond, Nat. Comm. 6 (2015) 8965, https://doi.org/10.1038/ncomms9965.
[16] D.A. Barskiy, A.M. Coffey, P. Nikolaou, D.M. Mikhaylov, B.M. Goodson, R.T. Branca, G.J. Lu, M.G. Shapiro, V. Telkki, V.V. Zhivonitko, et al., NMR hyperpolarization techniques of gases, Chem. Eur. J. 23 (2017) 725–751, https://doi.org/10.1002/chem.201603884.
[17] A. Henstra, T.-S. Lin, J. Schmidt, W.Th. Wenckebach, High dynamic nuclear polarization at room temperature, Chem. Phys. Lett. 165 (1990) 6–10, https://doi.org/10.1016/0009-2614(90)87002-9.
[18] W.Th. Wenckebach, Essentials of Dynamic Nuclear Polarization, NL, Spindrift, 2016.
[19] K. Takeda, Triplet state dynamic nuclear polarization; VDM Verlag Dr. Müller: Saarbrücken, DE, 2009.
[20] A.J. Van Strien, J. Schmidt, An EPR study of the triplet state of pentacene by electron spin-echo techniques and laser flash excitation, Chem. Phys. Lett. 70 (1980) 513–517, https://doi.org/10.1016/0009-2614(80)80115-1.
[21] H.-L. Yu, T.-S. Lin, S.I. Weissman, Time resolved studies of pentacene triplets by electron spin echo spectroscopy, J. Chem. Phys. 80 (1984) 102–107, https://doi.org/10.1063/1.446491.
[22] T.R. Eichhorn, N. Niketic, B. van den Brandt, U. Filges, T. Panzner, E. Rantsiou, W.Th. Wenckebach, P. Hautle, Proton polarization above 70% by DNP using photo-excited triplet states, a first step towards a broadband neutron spin filter, Nucl. Instrum. Methods Phys. Res. A 754 (2014) 10–14, https://doi.org/10.1016/j.nima.2014.03.047.
[23] K. Takeda, K. Takegoshi, T. Terao, Dynamic nuclear polarization by electron spins in the photoexcited triplet state: I. Attainment of proton polarization of 0.7 at 105 K in naphthalene, J. Phys. Soc. Jpn. 73 (2004) 2313–2318, https://doi.org/10.1143/JPSJ.73.2313.
[24] K. Tateishi, M. Negoro, S. Nishida, A. Kagawa, Y. Morita, M. Kitagawa, Room temperature hyperpolarization of nuclear spins in bulk, Proc. Natl. Acad. Sci. U.S.A. 111 (2014) 7257–7530, https://doi.org/10.1073/pnas.1315778111.
[25] A. Kagawa, M. Negoro, R. Ohba, N. Ichijo, K. Takamine, Y. Nakamura, T. Murata, Y. Morita, M. Kitagawa, Dynamic nuclear polarization using photoexcited triplet electron spins in eutectic mixtures, J. Phys. Chem. A 122 (2018) 9670–9675, https://doi.org/10.1021/acs.jpca.8b09934.
[26] K. Tateishi, M. Negoro, A. Kagawa, M. Kitagawa, Dynamic nuclear polarization with photoexcited triplet electrons in a glassy matrix, Angew. Chem. Int. Ed. 52 (2013) 13307–13310, https://doi.org/10.1002/anie.201305674.
[27] H. Kouno, Y. Kawashima, K. Tateishi, T. Uesaka, N. Kimizuka, N. Yanai, Nonpentacene polarizing agents with improved air stability for triplet dynamic nuclear polarization at room temperature, J. Chem. Phys. Lett. 10 (2019) 2208–2213, https://doi.org/10.1021/acs.jpclett.9b00480.
[28] K. Nishimura, H. Kouno, K. Tateishi, T. Uesaka, K. Ideta, N. Kimizuka, N. Yanai, Triplet dynamic nuclear polarization of nanocrystals dispersed in water at room temperature, Phys. Chem. Chem. Phys. 21 (2019) 16408–16412, https://doi.org/10.1039/c9cp03330k.
[29] M. Negoro, A. Kagawa, K. Tateishi, Y. Tanaka, T. Yuasa, K. Takahashi, M. Kitagawa, Dissolution dynamic nuclear polarization at room temperature using photoexcited triplet electrons, J. Phys. Chem. A 122 (2018) 4294–4297, https://doi.org/10.1021/acs.jpca.8b01415.
[30] A. Kagawa, Y. Murokawa, K. Takeda, M. Kitagawa, Optimization of ^{1}H spin density for dynamic nuclear polarization using photo-excited triplet electron spins, J. Magn. Reson. 197 (2009) 9–13, https://doi.org/10.1016/j.jmr.2008.11.009.
[31] K. Kouřil, H. Kouřilová, S. Bartram, M.H. Levitt, B. Meier, Scalable dissolution-dynamic nuclear polarization with rapid transfer of a polarized solid, Nat. Commun. 10 (2019), https://doi.org/10.5258/SOTON/D0837, 1733–1-6.
[32] M.L. Hirsch, N. Kalechofsky, A. Belzer, M. Rosay, J.G. Kempf, Brute-Force Hyperpolarization for NMR and MRI, J. Am. Chem. Soc. 137 (2015) 8428–8434, https://doi.org/10.1021/jacs.5b01252.
[33] J. Milani, B. Vuichoud, A. Bornet, P. Miéville, R. Mottier, S. Jannin, G. Bodenhausen, A magnetic tunnel to shelter hyperpolarized fluids, Rev. Sci. Instrum. 86 (2015), https://doi.org/10.1063/1.4908196.
[34] T.R. Eichhorn, Y. Takado, N. Salameh, A. Capozzi, T. Cheng, J.-N. Hyacinthe, M. Mishkovsky, C. Roussel, A. Comment, Hyperpolarization without persistent radicals for in vivo real-time metabolic imaging, Proc. Natl. Acad. Sci. U.S.A. 110 (2013) 18064–18069, https://doi.org/10.1073/pnas.1314928110.
[35] S. Kan, M. Fan, J. Courtieu, A single-coil triple resonance probe for NMR experiments, Rev. Sci. Instrum. 51 (1980) 887–890, https://doi.org/10.1063/1.1136352.
[36] K. Takeda, OPENCORE NMR: Open-source core modules for implementing an integrated FPGA-based NMR spectrometer, J. Magn. Reson. 192 (2008) 218–229, https://doi.org/10.1016/j.jmr.2008.02.019.
[37] G. Metz, X. Wu, S.O. Smith, Ramped-amplitude cross polarization in magic-angle-spinning NMR, J. Magn. Reson. A 110 (1984) 219–227, https://doi.org/10.1006/jmra.1994.1208.
[38] S. Bowen, C. Hilty, Rapid sample injection for hyperpolarized NMR spectroscopy, Phys. Chem. Chem. Phys. 12 (2010) 5766–5770, https://doi.org/10.1039/c002316g.
[39] J. Granwehr, R. Panek, J. Leggett, W. Köckenberger, Quantifying the transfer and settling in NMR experiments with sample shuttling, J. Chem. Phys. 132 (2010), https://doi.org/10.1063/1.3446804, 244507-1-13.
[40] H.-Y. Chen, C. Hilty, Implementation and characterization of flow injection in dissolution dynamic nuclear polarization NMR spectroscopy, Chem. Phys. Chem. 16 (2015) 2647–2652, https://doi.org/10.1002/cphc.201500292.
[41] K.R. Kehsari, J. Kurhanewicz, J.M. Macdonald, D.M. Wilson, Generating contrast in hyperpolarized 13 C MRI using ligand–receptor interactions, Analyst 137 (2012) 3427–3429, https://doi.org/10.1039/c2an35406c.
[42] M.H. Lerche, S. Meier, P.R. Jensen, H. Baumann, B.O. Petersen, M. Karlsson, J.Ø. Duus, J.H. Ardenkjær-Larsen, Study of molecular interactions with ^{13}C DNP-NMR, J. Magn. Reson. 203 (2010) 52–56, https://doi.org/10.1016/j.jmr.2009.11.020.