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Recent advances of ^{17}O NMR spectroscopy

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Abstract Study on the structure and dynamics of molecules at the atomic level is of great significance for understanding their function and stability as well as roles for various chemico-physical and biological processes. ^{17}O NMR spectroscopy has appeared as an elegant technique for investigating of the physicochemical and structural properties of oxygen-containing compounds such as metal organic frameworks and nanosized oxides. This method has drawn much attention as it provides unique insights into the properties of targets based on atomistic information of local oxygen environments which is otherwise difficult to obtain using other methods. In this mini review, we introduce and discuss the recent study and developments of ^{17}O NMR techniques which are tailored for the investigation on the structure and dynamics of water and inorganic materials.

Keywords ^{17}O NMR, water, inorganic materials

Introduction

Oxygen is one of the most fundamental elements in biological systems. ^{17}O NMR spectroscopy is an excellent and pivotal technique to detect the variations in the local environment of oxygen in organic and biological molecules. The first observation of ^{17}O signal dates back to 1950 in which the H_2O, D_2O, and some other liquids such as ethanol and methanol were detected.[4] However, compared to other conventional NMR techniques using ^{1}H, ^{13}C, and ^{15}N, ^{17}O NMR spectroscopy has not been largely applied to a number of research fields for the following reasons of ^{17}O: (1) the extremely low natural abundance (0.037%), (2) the nuclear spin quantum number (*I*) of 5/2, and (3) a very low magnetogyric ratio.[5-6] Therefore, the ^{17}O isotope enrichment, which is generally expensive, and the development of signal enhancement method have been considered to use ^{17}O as a probe.

In the last two decades, the application of ^{17}O NMR spectroscopy has been making a great progress due largely to the development of new NMR methods and the availability of high magnetic fields (e.g. 14.1 T). For magic-angle spinning (MAS) NMR, the inherently low spectral resolution of ^{17}O nuclei comes largely from the residual second-order nuclear quadrupolar interaction which cannot be eliminated by MAS, and, thereby, causing severe line broadening.[6] However, the application of a high magnetic field can attenuate the second-order nuclear quadrupolar interaction, and significantly enhances the overall resolution and sensitivity. Griffin and co-workers first demonstrated that dynamic nuclear polarization (DNP) methodology is remarkably useful for the enhancement of the signal of ^{17}O.[7] This observation stimulated subsequently a number of ^{17}O-based NMR studies using directly the natural

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abundance of ^{17}O.[7-11]

In this mini review, we describe comprehensively the recent development and application of ^{17}O NMR spectroscopy to explore the structure and dynamics of oxygen-containing molecules and compounds. We explain briefly ^{17}O NMR spectroscopy-based case studies, mostly on water and inorganic materials. Noteworthy, we will narrow our scope to the results reported in the last 5 years in order to provide the most recent understanding of the application of ^{17}O NMR techniques.

Study on water

Water, one the most abundant molecules on the surface of Earth, is essential for our daily life and involved in almost all chemico-physical, biological, and cellualr processes.[12] It has been well known that water molecules play fundamental and key roles in shaping, keeping, and controlling of the structures and dynamics of target molecules such as proteins and nucleic acids by impacting the intramolecular hydrogen bonds of target molecules as well as intermolecular hydrogen bonding networks between water and target molecules. ^{17}O NMR technique has shown its useful capability to investigate the water structure and dynamics. Previous studies using ^{17}O NMR spectroscopy demonstrated that the formation of water cluster is modulated by ions and temperature.[13] Thus, the continuous development and application of the ^{17}O NMR technique will be of fundamental value for the understanding of roles water in a number of fields at the atomistic level.

Of note, an insightful study has been reported. Griffin and co-workers succeeded in finding the structure and dynamics of bound water in barium chlorate monohydrate system.[14] They optimized ^{17}O NMR parameters for studying of water molecules, and, in addition, explained how torsional oscillations of the water molecules impact on the quadrupolar coupling constant (CQ) of ^{17}O using the variable temperature MAS NMR spectroscopy. Interestingly, at temperatures lower than ~150 K without ^{1}H decoupling, ^{1}H–^{17}O dipole splitting in spectra was detected due to the homogeneity between the ^{1}H–^{1}H

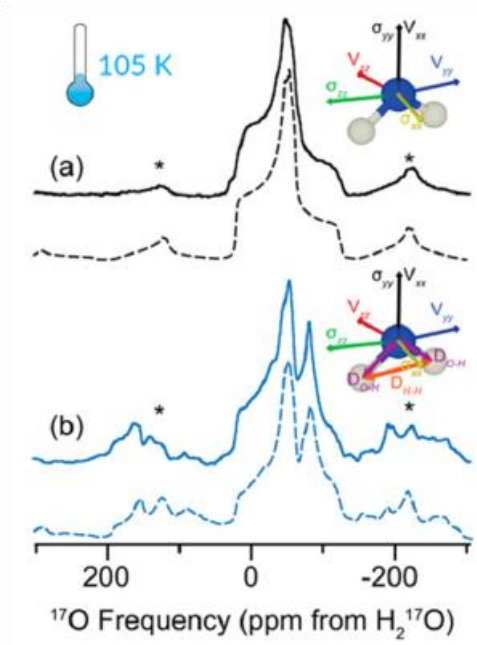

Figure 1. (**a** and **b**) ^{17}O MAS NMR spectra of bound water in barium chlorate monohydrate were obtained at 105 ± 5 K in the presence (**a**) and absence of 100 kHz continuous-wave ^{1}H decoupling (**b**). Asterisks (*) represent spinning sidebands. Reproduced with permission from Ref. [11]. Copyright 2016 American Chemical Society.

and two $^{1}H–^{17}O$ dipolar couplings. These results provided a further possibility to explore the structure of hydration water (**Figure 1**).[14] More recently, they reported the high resolution ^{17}O NMR spectra for lanthanum magnesium nitrate hydrate and successfully distinguished four distinct water in its crystal structure, exhibiting the ability to analyze structural water in hydrated crystal structures.[15] Considering the fact that water hydration is key for understanding protein folding, stability, functional dynamics, and even disease-causing protein misfolding and aggregation, a series of future studies of ^{17}O NMR are promising.

On the one hand, it was noteworthy that Makulski et al. investigated $H_2{}^{17}O$ molecules in the gas phase by using various gaseous solvent with different solvent densities.[16] The dependences of ^{17}O chemical shift and spin-spin coupling on the solvent density were rigorously monitored. They for the first time could set best parameters for various $H_2{}^{17}O$ NMR measurements in the gas phase by ruling out influences of intermolecular interactions between $H_2{}^{17}O$ molecules. In addition, the study provided us with further insights into NMR parameters of a single $H_2{}^{17}O$ molecule such as ^{17}O chemical shifts and $^{1}J_0(^{17}O, ^{1}H)$.

Study on inorganic materials

Inorganic materials have been widely used due to their useful properties including energy storage[17] and heterogeneous catalysis.[18] Considering the significant importance of inorganic materials in a large number of research and industrial fields, the accumulation of structural and dynamic information of inorganic materials is inevitable. The first study on inorganic materials using ^{17}O NMR spectroscopy was reported in 1983, and the nature of the M-O bond was suggested to influence the quadrupole interaction in this early work.[19] In 1990s, continuous developments of NMR methodologies with the improvement of the

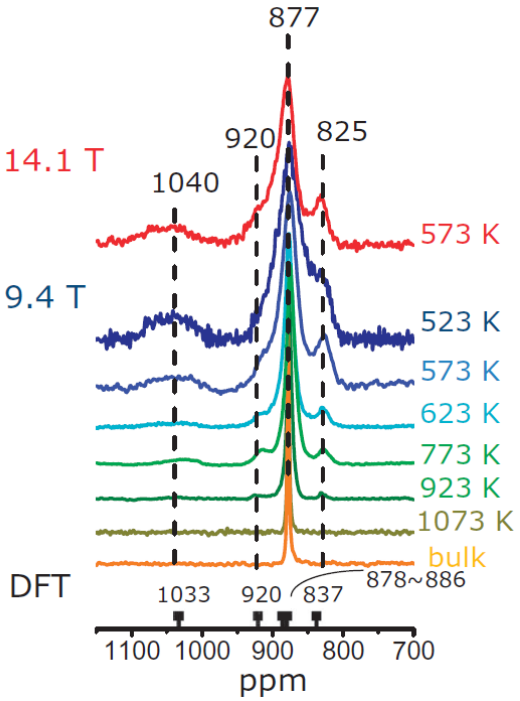

Figure 2. ^{17}O NMR spectra of ceria nanoparticle. ^{17}O NMR spectra for ceria nanoparticles were acquired at temperatures ranging from 523 to 1073 K and at two external magnetic fields, 9.4T and 14.1 T. In comparison, the predicted chemical shifts for oxygen ions of nanosized ceria based on density functional theory (DFT) calculation were displayed. Re-produced with permission from Ref. [20]. Reprinted with permission from AAAS.

magnetic field stimulated numerous studies on inorganic materials such as hydroxyl species,[20] ceramic superconductors,[21] and phosphate crystals and glasses[22] using ^{17}O NMR spectroscopy. These studies provided practical and comprehensive understanding of the physicochemical properties of these materials. Collectively, ^{17}O NMR spectroscopy is an efficient tool to probe the oxygen-containing inorganic materials.

In 2015, Wang et al. reported the first ^{17}O NMR study to identify different oxygen species in the nanosized oxides.[23] The authors developed a novel NMR strategy to monitor the spectra of nanosized ceria, which benefited the further investigations on the local structure and chemical property of surfaces of nano-sized ceria. The results exhibited that the ^{17}O signals of the oxygen ions at the first, second, and third surface layers, hydroxyl sites, and oxygen ions in bulk have different chemical shift values (**Figure 2**). In addition, the variations of ^{17}O spectra of ceria nanoparticles depending on temperature were also monitored, which gave us chemical and molecular origins on the interconversion between different oxygen ions with the change in temperature.

In 2017, Perras et al. successfully determined the precise length of O-H bond in hydroxyl groups of silica and silica–alumina compounds through ^{17}O DNP surface-enhanced NMR spectroscopy (SENS).[8] This method overcame the sensitivity limit of ^{17}O, which led to the marked enhancement in the signal of ^{17}O even without isotope enrichment. The results exhibited that the distances of O-H bond determined using ^{17}O NMR was in sub-pm precision, and these lengths correlated well with the acidity of catalysts, which was measured using the potentiometric titration.

Conclusion

Although ^{17}O NMR spectroscopy has been developed almost 70 years ago, it attracted much less attention than conventional ^{1}H, ^{13}C, and ^{15}N NMR spectroscopy. However, the field of ^{17}O NMR spectroscopy has been increasingly recognized as a key approach for the study of $^{(17)}$O-containing molecules, and, shown a rapid progress in the last decade due to the development of NMR spectrometer with higher magnetic fields,[24] NMR methodologies,[9,11] and new methods of ^{17}O labeling.[25-26] The recent case studies addressed in this review clearly demonstrate the usefulness and development of ^{17}O NMR spectroscopy for exploring the structure and dynamics of oxygen-containing molecules. Furthermore, recent two-dimensional NMR spectra of ^{17}O-^{15}N and ^{17}O-^{13}C of a dipeptide, N-acetyl-L-valyl-L-leucine, showed a possibility of the application of ^{17}O NMR spectroscopy to biological systems.[15] We anticipate more active developments of the ^{17}O NMR technique and insightful studies on protein function, disease-causing protein aggregation, and water structures.

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