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Quasi-elastic neutron scattering studies on fast dynamics of water molecules in tetra-*n*-butylammonium bromide semiclathrate hydrate

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ABSTRACT

The dynamics of the water molecules in tetra-*n*-butyl-*d*36-ammonium bromide semiclathrate hydrate were investigated by quasi-elastic neutron scattering (QENS). The QENS results clearly revealed a fast reorientation motion of water molecules in the temperature range of 212–278 K. The mean jump distance of hydrogen atoms was within 1.5–2.0 Å. The relaxation time of water reorientation was estimated to be 100–410 ps with activation energy of 10.2 ± 5.8 kJ·mol⁻¹. The activation energy was in good agreement with the cleavage energy of hydrogen bonds. Such a short relaxation time of water reorientation is possibly due to strong interaction between a bromide anion and its surrounding water molecules (similar to so-called negative hydration), which suggests a unique strategy for designing efficient, safe, and inexpensive proton conductors having the framework of semiclathrate hydrates.

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Proton conduction phenomenon in ices has attracted many researchers due to unusually-active dynamic behaviors of water molecules in the crystalline compounds. Remarkably, it is known that the proton conductivity in ice I_h (10^{-6} – 10^{-7} S·cm⁻¹) is higher than in liquid water¹⁻⁴ and the conduction mechanism in crystalline ices is considered to be fundamentally different from liquid water.⁵⁻⁸ Clathrate hydrate also shows proton conduction phenomenon⁹⁻¹², in which hydrogen-bonded networks of water molecules form the crystal framework, as in the case of ices. Various properties of clathrate hydrates can be designed by selecting guest species to be enclathrated into hydrate cages. In fact, even ionic guest species are allowed to be enclathrated, which enhances the proton conduction; clathrate hydrates formed with perchloric acid or hexafluorophosphoric acid, which supplies the large number of protons, are known as the proton conductors with a conductivity (about 10^{-3} S·cm⁻¹ or 10^{-1} S·cm⁻¹ at 273 K,^{13,14} respectively) higher than ices. However, these aqueous solutions with strongly acidity are difficult to handle and limited in their applications. Therefore, establishing a strategy to design well-proton-conducting clathrate hydrate from easily handled guest species is an important task for its future and practical applications.

As a way to solve the task, we have focused on semiclathrate hydrates (or ionic clathrate hydrates). Semiclathrate hydrate is a crystalline inclusion compound, in which quaternary ammonium or phosphonium cation is incorporated into hydrate cages. The counter anions take part in the hydrogen-bonded networks as part of the host substance with water molecules.^{15,16} Among

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easily handled semiclathrate hydrates, tetra-*n*-butylammonium bromide (TBAB) semiclathrate hydrate^{15,17,18} has the relatively high electrical conductivity.^{19,20} Therefore, semiclathrate hydrates have been considered to be one of the promising candidates for highly conductive solid electrolytes.¹⁹⁻²¹ Recently, we reinforced this consideration by revealing that the proton was the charge carrier, which induces the proton conductivity of $4.1 \times 10^{-6} \text{ S} \cdot \text{cm}^{-1}$ at 273 K, in the case of single-crystalline TBAB semiclathrate hydrate.²⁰

Though TBAB semiclathrate hydrate has a proton conductivity^{19,20} higher than that of ices or general clathrate hydrates (so-called gas hydrates, consisting of non-ionic molecules such as CH₄ or CO₂¹²), the relaxation time of water molecules in TBAB semiclathrate hydrate obtained by a nuclear magnetic resonance (NMR) was observed to be almost the same as that of ices or general clathrate hydrates.²² This apparent discrepancy suggests that a hidden mechanism of proton transfer would have enhanced the conductivity in TBAB semiclathrate hydrate, since the number of protons in it may not be so much increased compared with the general clathrate hydrates. To find the answer, it is necessary to analyze the water reorientation motion in a frequency window wider than that measurable by NMR. This is because the mechanism of the proton transfer in the clathrate hydrates or ices reflects the nature of water dynamics, especially of molecular reorientation motion.^{1-11,20,22-24}

In the present study, to reveal the role of fast water dynamics for inducing a conductivity higher than ices or clathrate hydrates, we conducted quasi-elastic neutron scattering (QENS)

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measurement of the TBAB semiclathrate hydrate. QENS (the measurable time window is from picosecond to nanosecond) allows us to investigate the molecular dynamics much faster than that of NMR (nanosecond to microsecond). In the previous QENS studies on the water dynamics in clathrate hydrates, Desmedt et al. reported the reorientation motion of 700 ps at 220 K in the fast-proton-conducting perchloric acid clathrate hydrate.¹⁰ Occurrence of the long-range proton diffusion, accompanied with the reorientation motion, has been also reported in some other types of clathrate hydrate and ice by QENS, where the dynamics in a timescale from picosecond to nanosecond orders have been observed.^{9-11,25} Nevertheless, there is no report on QENS results of TBAB semiclathrate hydrate.

The large difference of incoherent neutron scattering cross section between a hydrogen and a deuterium make it possible to observe the dynamics of the water molecules selectively, therefore, perdeuterated tetra-*n*-butyl-*d*36-ammonium bromide semiclathrate hydrate (*d*-TBAB·26H₂O) was used. *d*-TBAB (99.5 atomic%) was obtained from C/D/N Isotopes Inc. *d*-TBAB·26H₂O was carefully prepared at 285.0 K to prevent the formation of metastable crystals, *i.e.* TBAB·38H₂O.¹⁶ Obtained crystal was quenched and powdered at a liquid nitrogen temperature. The sample was wrapped in aluminum foil (~10 μm thick) to maintain a thin-walled annular geometry in bulk. The foil-wrapped sample was placed in an aluminum cell (a thickness of 0.25 mm and an inner diameter of 14.0 mm). The cell was mechanically sealed with an indium wire under dry helium atmosphere

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(purity: 0.999999) equipped at low-temperature room kept at 263 K. The sample cell was stored in a dry-shipper at 77 K just before the measurement.

The QENS measurements were carried out using the near-backscattering spectrometer (DNA) at Materials and Life Science Experimental Facility (MLF), Japan Proton Accelerator Research Complex (J-PARC) with high signal-to-noise ratio and high energy resolution.²⁶ The energy resolution was 3.6 μeV using the Si(111) analyzer. The measured momentum transfer (Q) and energy transfer (ΔE) ranges were $0.1 < Q < 1.9 \text{ \AA}^{-1}$ and $-40 < \Delta E < 100 \text{ \mu eV}$, respectively. The cell was quickly mounted on a sample stick, and then the stick was inserted in a top-loading-type cryo-furnace equipped at the DNA which was controlled at 100 K to prevent dissociation of the sample. No condensation of bulk water was confirmed by temperature dependence of the elastic intensity, as shown in Supplementary material Figure S1. The QENS was measured at 212 K, 232 K, 252 K, 272 K, and 278 K. The resolution function, $R(Q, \omega)$, was measured at 8 K, where we assumed that all dynamics were frozen. A typical measurement duration was around 4 hours at 700 kW proton beam power. An empty cell was measured at 300 K to subtract background from the container.

The obtained Q - ΔE maps are shown in Figure 1(a). A Bragg peak was observed at $Q = 0.6 \text{ \AA}^{-1}$ at elastic position ($\Delta E = 0$) in all measured data. The profile of the elastic intensity was shown in Supplementary material Figure S2. The peak position agreed with the literature value (0.6 \AA^{-1}) of TBAB semicathrate hydrate (TBAB \cdot 26H₂O: tetragonal structure, space group: P4/ mmm),^{27,28} which

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indicates the existence of d -TBAB·26H₂O in the whole range of measurement temperature. The intensity corresponding to QENS was observed in the inelastic region at temperatures above 212 K. The QENS intensity increased and broadened with an increase in temperature. The representative QENS profiles ($S(Q, E)$ at $Q = 0.875 \text{ \AA}^{-1}$) are also shown in Figure 1(b). The narrow elastic and the broad quasi-elastic components were observed. Since the ratio of incoherent scattering cross section of water is 87 % to the total scattering cross section of d -TBAB·26H₂O, the observed intensity corresponds to the hydrogen of water in d -TBAB·26H₂O and reflects the dynamics of water. The elastic and quasi-elastic components derived from immobile and mobile hydrogen, respectively. The QENS profile was deconvoluted into elastic and quasi-elastic components using Equation (1).^{9-11,29}

$$S(Q, \omega) = [A_D(Q)\delta(\omega) + A_L(Q)L(\Gamma_L, \omega)] \otimes R(Q, \omega) + BG(Q) \quad (1)$$

The elastic component and the quasi-elastic component were represented by delta function (δ) and Lorentzian function (L), respectively. The A_D and A_L are the coefficients of delta and Lorentzian functions, respectively. Γ_L is half width at half maximum of Lorentzian function. BG represents the background. The fitting results are also shown in Figure 1(b).

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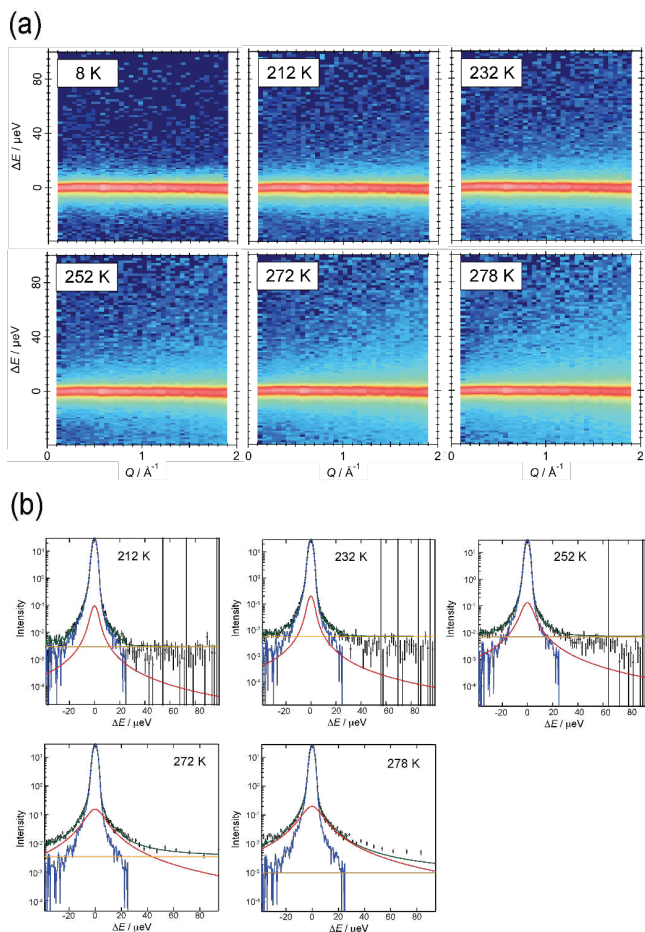


Figure 1. (a) Q - ΔE maps of d -TBAB·26H₂O obtained by QENS measurement. The red-colored region means the high scattering intensity. (b) The representative Q -sliced QENS profiles at $Q = 0.875 \pm 0.075 \text{ \AA}^{-1}$ measured at 212 K, 232 K, 252 K, 272 K, and 278 K. Fitting results were shown as fitted function (green), delta function (blue), Lorentzian function (red), and background (orange).

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Figure 2 shows the half width at half maximum (Γ_L) of the Lorentzian function ($L(\Gamma_L, \omega)$) plotted as a function of Q . The linewidth was independent of Q . This result implies that the mobile hydrogen atoms are localized in a limited space.

The relaxation time (τ) of hydrogen dynamics was estimated from the linewidth (Figure 2) using Equation (2).

$$\tau = \frac{1}{2\pi\Gamma_L \times (2.418 \times 10^{11})} \quad (2)$$

The obtained relaxation time (Figure 3) was 100–410 ps at 278–212 K. The estimated activation energy E_a was 10.2 ± 5.8 kJ·mol⁻¹, which is close to the cleavage energy of hydrogen bonds between water molecules.²⁴

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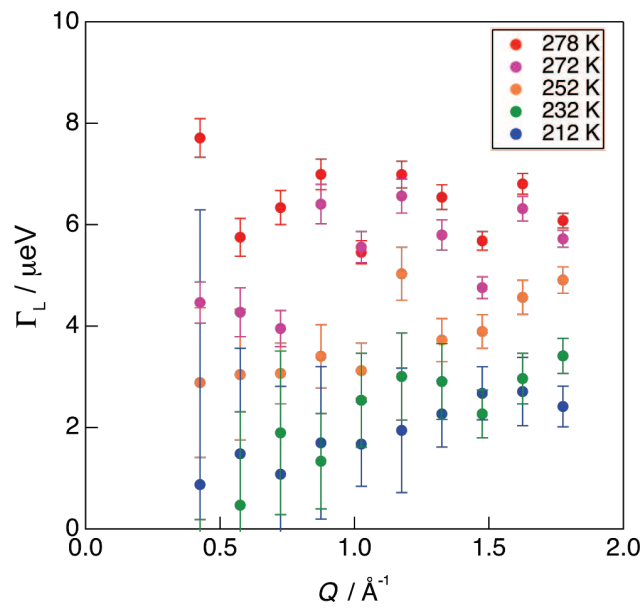


Figure 2. The half width at half maximum (Γ_L) of the Lorentzian function ($L(Q,\omega)$) plotted as a function of Q . The Γ_L was independent of Q . Such trend implies that the mobile space of the hydrogen atoms is limited.

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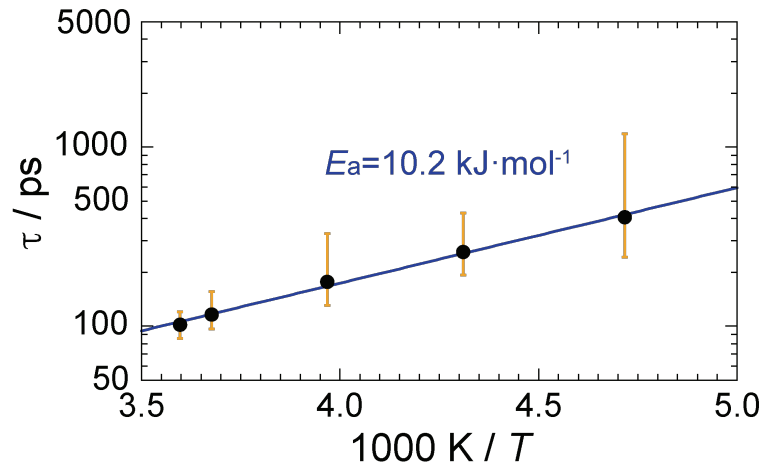


Figure 3. Arrhenius plots of the relaxation time (τ) of hydrogen dynamics observed by QENS measurement. The estimated activation energy was $10.2 \pm 5.8 \text{ kJ}\cdot\text{mol}^{-1}$, which showed good agreement with the cleavage energy of hydrogen bonds.

An elastic incoherent structure factor (EISF) was expressed as Equation (3) and shown in

Figure 4 (a).

$$EISF = \frac{A_D}{A_D + A_L} \quad (3)$$

The fitting curves of EISF were drawn by using jumping model between two sites, which showed the highest accuracy among 2–4 sites, and the results in ref 25.

$$EISF(Q) = f + (1 - f) \left[\frac{1}{2} (1 + j_0(Qd)) \right] \quad (4)$$

The symbols f , j_0 , and d stand for the fraction of immobile hydrogen, Bessel function of zeroth order, and jump distance between two sites, respectively. Supplementary material Figures S3 and S4 show the fitting results of EISF with various d values from 1.0 to 2.8 Å. The EISF results fitted

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well with the mean jump distance between 1.5–2.0 Å. As the representative data, the fitting results ($d = 1.8$ Å) of EISF were shown in Figure 4 (a). The obtained mean jump distance (1.5–2.0 Å) agreed well with the reorientation distance of hydrogen atoms around the oxygen atom of water molecules (1.5–1.8 Å),^{9,25} whereas it was different from the jump distances of proton transfer and long-range proton diffusion, which should be about 1.0 Å (H···O distance) and about 2.8 Å (O···O distance), respectively.

The mechanism of the proton transfer in the clathrate hydrates or ices is related with the water dynamics, especially molecular reorientation motion.^{1-11,20,23} At Bjerrum defects, proton transfer is temporarily suspended, where the reorientation of the water molecules (or hydronium ions) is necessary to restart the transfer. In other words, the reorientation of water molecules so as to alleviate the defects is a rate-limiting step of proton conduction.²³ The relaxation times obtained by QENS in TBAB·26H₂O were much shorter than the relaxation time (approximately 0.5 μs³⁰ or 12 μs²⁰ at 273 K) obtained by NMR measurement, although both the activation energies of QENS and NMR were similar to the cleavage energy of hydrogen bonds (about 14 kJ·mol⁻¹)²⁴ rather than proton (ionic defect) generation energy (approximately 70 kJ·mol⁻¹)^{31,32}. In fact, such the reorientation motion of water with hundreds of picosecond order has been universally observed in the other type of ionic clathrate hydrate (HClO₄·5.5H₂O),¹⁰ which is a well-known ionic conductor. The jump distance, the relaxation time, and the activation energy of HClO₄·5.5H₂O are 1.45 Å,

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700 ± 100 ps, and 17.4 ± 1.5 kJ·mol⁻¹ at 220 K. The results obtained in the present study are similar to these values in HClO₄·5.5H₂O, suggesting that the semiclathrate hydrate can be as useful as the ionic clathrate hydrate.

Figure 4 (b) shows the f in the Equation (4) corresponding to immobile water molecules. The fraction of immobile water molecules depended strongly on the temperatures. Around 220 K, the ratio of mobile water molecules was only 4 %. Near the dissociation temperature of d -TBAB·26H₂O, the mobile water population increased to 18 %. This ratio of 18 % means that approximately five water molecules per 1 unit (d -TBAB·26H₂O) near the dissociation temperatures are in motion, whereas the ratio of 4 % around 220 K corresponds to a single water molecule per 1 unit. The trend of its temperature dependence is reasonable to qualitatively explain the temperature dependence of the electrical conductivity in TBAB·26H₂O at 270-286 K²⁰. The five water molecules are close to the number of water molecules coordinating around the bromide anion. Such results mean that the bromide anion activates the reorientation motion of the water molecules locally in TBAB·26H₂O, which resembles a negative hydration around bromide anion in the aqueous solution. Considering the results of NMR measurement, the other water molecules rotate more slowly (Figure 5).

The features of hydrogen dynamics in d -TBAB·26H₂O interpreted from the perspectives of jump distance, activation energy, relaxation time, and ratio of water molecules contributing

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QENS can be summarized as follows: (1) the hydrogen is locally transferred; (2) the hydrogen jump distance between two sites is within 1.5–2.0 Å; (3) the activation energy is $10.2 \pm 5.8 \text{ kJ} \cdot \text{mol}^{-1}$, which is close to the cleavage energy of hydrogen bonds; (4) the relaxation time is 100–410 ps; (5) the ratio of water molecules contributing to QENS is 4–18 %. These results revealed that the signals observed by QENS measurement are derived from the fast (hundreds of ps order) reorientation motion of the water molecules around bromide anions in TBAB·26H₂O. The μs-order reorientation motion measurable by NMR are detected in the general clathrate hydrate and ice as well as TBAB·26H₂O. Unlike the μs-order reorientation motion obtained by NMR, the hundreds-of-ps-order reorientation motion obtained in TBAB·26H₂O by QENS could make the proton transfer more smoothly in the region around bromide ion. As mentioned above, proton transfer is temporarily suspended at Bjerrum defects. To restart the proton transfer, that is, to alleviate the defects, the reorientation motion of water molecules is inevitably required. The fast water reorientation motion obtained in TBAB·26H₂O by QENS would contribute to shortening the residence time of proton at the Bjerrum defects accidentally formed around bromide ion. This would be the reason why the TBAB·26H₂O had a bulk proton conductivity higher than the general clathrate hydrates and ices.

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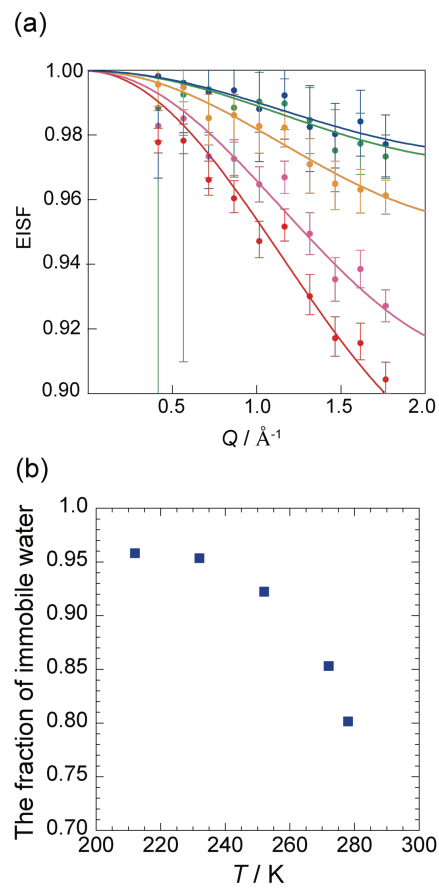


Figure 4 (a) EISF results plotted as Q . The fitting curves were calculated using Equation (4) with $d = 1.8 \text{ \AA}$. The colors reflect the temperatures, such as 212 K (blue), 232 K (green), 252 K (orange), 272 K (pink), and 278 K (red). (b) The immobile fraction in the Equation (4) corresponding to immobile water in d -TBAB \cdot 26H $_2$ O. The fraction depended strongly on the temperatures.

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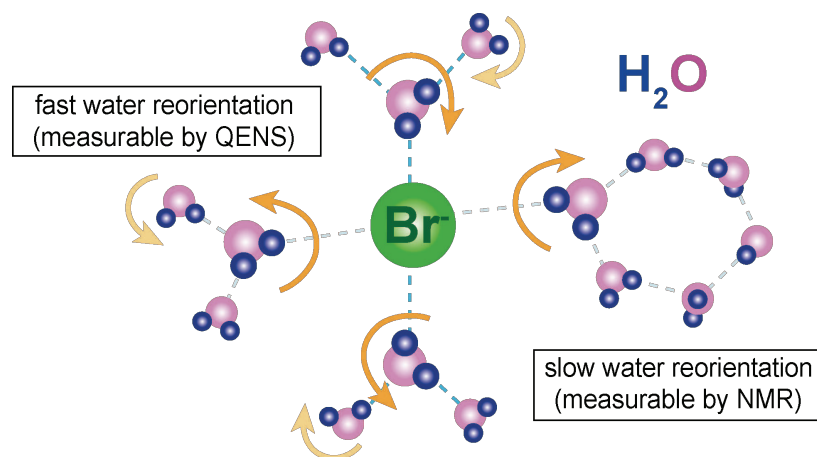


Figure 5. Illustration of the dynamics of the water molecules around bromide anions (measurable by QENS) and the other water molecules (by NMR) in TBAB·26H₂O. The fast water reorientation around bromide anions represents the negative hydration-like region, whereas the slow water reorientation in the other water molecules stands for the rigid hydrogen-bonded region.

In summary, the reorientation motion on the order of some hundreds of picoseconds was observed in TBAB semiclathrate hydrate (*d*-TBAB·26H₂O) by QENS measurement. Such relaxation times obtained by QENS are much shorter than that of the order of microseconds previously obtained by NMR for the same medium. The fast water reorientation should be caused by the negative hydration-like behavior of the water molecules surrounding bromide anion. Why TBAB semiclathrate hydrate exhibits the high proton conductivity would be originated from this fast water reorientation motion around bromide ion observed by QENS. The results provided the tips to

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improve the conductivity of semiclathrate hydrates and suggested the possibility of unconventional applications such as solid-state electrolytes.

Supplementary material

See the supplementary material for experimental data including an elastic intensity of d -TBAB·26H₂O and the fitting results of EISF with various d values.

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Author Declarations

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

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Jin Shimada: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Funding acquisition (equal); Investigation (equal); Validation (equal); Writing – original draft (equal); Writing – review & editing (equal).

Atsushi Tani: Conceptualization (equal); Funding acquisition (equal); Investigation (equal); Project administration (equal); Supervision (equal); Validation (equal); Writing – review & editing (equal).

Takeshi Yamada: Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Project administration (equal); Validation (equal); Writing – original draft (equal); Writing – review & editing (equal).

Takeshi Sugahara: Funding acquisition (equal); Supervision (equal); Validation (equal); Writing – review & editing (equal).

Takayuki Hirai: Supervision (equal); Writing – review & editing (equal).

Takuo Okuchi: Funding acquisition (equal); Project administration (equal); Supervision (equal); Writing – review & editing (equal).

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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References

- ¹ H. Gränicher, C. Jaccard, P. Scherrer and A. Steinemann, *Discuss. Faraday Soc.*, 23, 50 (1957).
<https://doi.org/10.1039/DF9572300050>
- ² M. Eigen and L. De Maeyer, *Proc. R. Soc. Lond. A*, 247, 505 (1958).
<https://doi.org/10.1098/rspa.1958.0208>
- ³ M. Eigen, *Angew. Chem. Int. Ed. Eng.* 3, 1 (1964). <https://doi.org/10.1002/anie.196400011>
- ⁴ J. W. Glen, J. G. Paren, *J. Glaciol.* 15, 15 (1975). <https://doi.org/10.3189/S0022143000034249>
- ⁵ C. Jaccard, *Helv. Phys. Acta*, 32, 89 (1959). <https://doi.org/10.3929/ETHZ-A-000099624>.
- ⁶ C. Jaccard, *Eur. Phys. J. B* 3, 99 (1964). <https://doi.org/10.1007/BF02422356>.
- ⁷ C. Jaccard, *Ann. N. Y. Acad. Sci.* 125, 390 (1965). <https://doi.org/10.1111/j.1749-6632.1965.tb45405.x>.
- ⁸ L. Onsager and M. Dupuis, *The Electrical Properties of Ice*. In *Electrolytes*; Pesce, B., Ed.; Pergamon Press: Oxford (1962).
- ⁹ A. Desmedt, F. Stallmach, R. E. Lechner and M. A. Gonzalez, *J. Chem. Phys.* 121, 11916 (2004).
<https://doi.org/10.1063/1.1819863>
- ¹⁰ A. Desmedt, R. E. Lechner, Jean-Claude Lassegues, F. Guillaume, D. Cavagnat and J. Grondin, *Solid State Ionics* 252, 19 (2013). <https://doi.org/10.1016/j.ssi.2013.06.004>

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PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.5157560

- ¹¹ L. Bedouret, P. Judeinstein, J. Ollivier, J. Combet and A. Desmedt, *J. Phys. Chem. B* 118, 13357 (2014). <https://doi.org/10.1021/jp504128m>
- ¹² L. A. Stern, S. Lu, R. Constable, W. L. Du Frane, and J. J. Roberts, *Geophys. Res. Lett.* 48, e2021GL093475, (2021). <https://doi.org/10.1029/2021GL093475>
- ¹³ J.-H. Cha, K. Shin, S. Choi, S. Lee and H. Lee, *J. Phys. Chem. C*, 112, 35, 13332 (2008). <https://doi.org/10.1021/jp805510g>
- ¹⁴ M. Cappadonia, A. A. Kornyshev, S. Krause, A. M. Kuznetsov and U. Stimming, *J. Chem. Phys.*, 101, 7672–7682 (1994). <https://doi.org/10.1063/1.468260>
- ¹⁵ W. Shimada, M. Shiro, H. Kondo, S. Takeya, H. Oyama, T. Ebinuma and H. Narita, *Acta Cryst. C* 61, o65 (2005). <https://doi.org/10.1107/S0108270104032743>
- ¹⁶ T. V. Rodionova, I. S. Terekhova and A. Y. Manakov, *Energy Fuels* 36, 18, 10458 (2022). <https://doi.org/10.1021/acs.energyfuels.2c01221>
- ¹⁷ H. Machida, T. Sugahara and I. Hirasawa, *CrystEngComm*, 20, 3328 (2018). <https://doi.org/10.1039/c8ce00190a>
- ¹⁸ H. Oyama, W. Shimada, T. Ebinuma, Y. Kamata, S. Takeya, T. Uchida, J. Nagao and H. Narita, *Fluid Phase Equilibria*, 234, 131 (2005). <https://doi.org/10.1016/j.fluid.2005.06.005>
- ¹⁹ Z. Borkowska, M. Opallo, A. Tymosiak-Zielinska and P. Zoltowski, *Colloids Surf, A Physicochem. Eng. Asp.* 134, 67 (1998). [https://doi.org/10.1016/S0927-7757\(97\)00328-2](https://doi.org/10.1016/S0927-7757(97)00328-2)

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- ²⁰ J. Shimada, Y. Takaoka, T. Ueda, A. Tani, T. Sugahara, K. Tsunashima, H. Yamada and T. Hirai, *Solid State Ionics, Solid State Ionics*, 393, 116188-1-8(2023).
<https://doi.org/10.1016/j.ssi.2023.116188>
- ²¹ N. Kuriyama, T. Sakai, H. Miyamura, A. Kato, and H. Ishikawa, *Solid State Ionics*, 40/41, 906, (1990). [https://doi.org/10.1016/0167-2738\(90\)90150-P](https://doi.org/10.1016/0167-2738(90)90150-P)
- ²² E.D. Sloan, C.A. Koh, *Clathrate Hydrates of Natural Gases*, 3rd ed., CRC press, Boca Raton, FL (2008).
- ²³ Du Hyeong Lee and H. Kang, *J. Phys. Chem. B*, 125, 8270 (2021).
<https://doi.org/10.1021/acs.jpcc.1c04414>
- ²⁴ N. Agmon, *Chem. Phys. Lett.* 244, 456, (1995). [https://doi.org/10.1016/0009-2614\(95\)00905-J](https://doi.org/10.1016/0009-2614(95)00905-J)
- ²⁵ I. Presiado, J. Lal, E. Mamontov, A.I. Kolesnikov and D. Huppert, *J. Phys. Chem. C*, 115, 20, 10245 (2011) <https://doi.org/10.1021/jp2008094>
- ²⁶ K. Shibata, N. Takahashi, Y. Kawakita, M. Matsuura, T. Yamada, T. Tominaga, W. Kambara, M. Kobayashi, Y. Inamura, T. Nakatani, K. Nakajima and M. Arai, *JPS Conf. Proc.* 8, 036022 (2015).
<http://dx.doi.org/10.7566/JPSCP.8.036022>
- ²⁷ M. Oshima, M. Kida, and J. Nagao, *J. Chem. Eng. Data* 61, 9, 3334 (2016).
<https://doi.org/10.1021/acs.jced.6b00386>
- ²⁸ T. V. Rodionova, V. Yu. Komarov, G. V. Villevald, T. D. Karpova, N. V. Kuratieva and A. Yu.

This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.5157560

Manakov, J. Phys. Chem. B 117, 36, 10677 (2013). <https://doi.org/10.1021/jp406082z>

²⁹ T. Okuchi, N. Tomioka, N. Purevjav and K. Shibata, J. Appl. Cryst. 51, 1564 (2018).

<https://doi.org/10.1107/S1600576718013158>

³⁰ S. Schildmann, A. Nowaczyk, B. Geil, C. Gainaru and R. Böhmer, J. Chem. Phys. 130, 104505

(2009). <https://doi.org/10.1063/1.3081897>

³¹ J. H. Bilgram and H. Gränicher, Phys. Cond. Matter 18, 275 (1974).

<https://doi.org/10.1007/BF01464397>

³² I. Takei and N. Maeno, J. Phys. Colloques 48, C1-121 (1987).

<https://doi.org/10.1051/jphyscol:1987118>