This article can be cited before page numbers have been issued, to do this please use: S. Lam, Q. Li, J. P. Mailoa, C. Forsberg, R. Ballinger and J. Li, J. Mater. Chem. A, 2021, DOI: 10.1039/D0TA10576G.

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The Impact of Hydrogen Valence on Its Bonding and Transport in Molten Fluoride Salts

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Abstract

Interest in molten salts has increased significantly over the last decade due to their potential application in various clean-energy technologies including hydrogen generation, solar heat storage, advanced fission nuclear power plants, and compact fusion energy systems. In nuclear fission and fusion power plants, high heat capacity molten salts allow operation at high temperature and atmospheric pressure, which could dramatically increase efficiency, reduce capital cost, and enable passive safety features. In many of these systems, the hydrogen isotope is of particular importance due to its ability to corrode structural materials as $^3$H$^+$ in fluoride salts, and its potential to cause significant radioactive release as diffusive $^3$H$^0$, which are cited as key barriers to technological deployment. Yet, the chemistry and transport behavior of the hydrogen species remain poorly understood due to the difficulties in handling toxic salts and radioactive materials. Here, using ab initio molecular dynamics, we present a coupled examination of hydrogen speciation in the most common prototypical salts 66.6%LiF-33.3%BeF$\text{}_2$ (Flibe) and 46.5%LiF-11.5%NaF-42%KF (Flinak). Using extensively validated calculations on the local structure and dynamics, we find significant difference between $^3$H$^0$ and $^3$H$^+$ transport behaviors that are usually overlooked. We find that $^3$H$^0$ diffuses 3-5 times faster than $^3$H$^+$, which can be ascribed to hydrogen bonding and complexation in solution. This work explains contradicting experimental results and provides useful species transport data for designing hydrogen capture and corrosion control systems for molten salts.

Keywords: nuclear energy, molten salt, hydrogen bonding, atomistic simulation, structure-property relationship
Introduction

Interest in high-temperature molten salts has greatly increased in the last decade due to their application in a variety of emerging clean energy technologies including thermal storage, hydrogen production, batteries, fuel cells, and nuclear power [1][2][3][4][5]. In many of these salt systems, corrosion remains a central challenge [6]. This is particularly true for halide salts where corrosion impurities are soluble in the salt and a passivation layer between the structural materials and working fluid is thermodynamically unstable. In halide salts, atmospheric impurities such as hydrogen, oxygen, moisture and hydroxides are thermodynamically unstable and are consequently chemically reduced by the corrosion of metallic components of structural materials [7][8]. The presence of impurities has been shown to cause high rates of initial corrosion, resulting in significant mass loss and material degradation [9].

Fluoride molten salts are of particular interest in the development of next-generation nuclear reactors, since they offer a combination of high heat capacity, high boiling point, and low neutron absorption [10]. While existing water-cooled nuclear power generates more than 50% of the carbon-free electricity in the U.S. today, total nuclear capacity is projected to steadily decrease towards 2050 and new nuclear installations will be limited by concerns of safety, and economic viability [11][12]. A step change improvement in nuclear technology is therefore required for nuclear power to significantly contribute to decarbonization of the electrical grid. Thus, there has been a significant push towards the development of advanced molten salt nuclear systems, which could enable greatly increased heat removal, thermodynamic efficiency, and operation at near-atmospheric pressure. As a result, the use of molten salts could enable design simplification, economic competitiveness, and inherent safety via passive heat rejection.
Molten-salt cooled advanced reactors of all types have proposed the use of lithium-based salts since the addition of lithium depresses the melting point, making them easier to handle [13][14][15]. Among candidate salts, 66.6LiF-33.3BeF$_4$ (Flibe) and 46.5LiF-11.5KF-42NaF (Flinak) are the most popular choices for their superior heat transfer properties [16][17]. One of the greatest known challenges however, is that radioactive tritium ($^3$H) is generated by the neutronic reaction $^6$Li +n→$^4$He + $^3$HF [18]. The presence of $^3$HF drives up the redox potential in the system [7], which causes corrosion of metallic species such as chromium via the equilibrium reaction: $^3$HF$_{(g)}$ +Cr$_{(s)}$⇌CrF$_2$(soln) + $^3$H$_2$$_{(g)}$, forming diatomic tritium gas. The relative concentration of the $^{M_{\text{ox}}}$/M ($M=\text{Cr, Fe, Ni or other structural metals}$) and HF/H$_2$ couples depend on the temperature and redox potential, which is established by the Nernst equation. The diffusion of hydrogen into structural materials can cause hydrogen-induced embrittlement. Furthermore, temperature-driven precipitation of corrosion products like CrF$_2$ leads to heat exchanger fouling and the presence of these dissolved species can also change the physical, thermodynamic and chemical properties of a molten salt mixture [8]. In order to minimize oxidation in structural steels, the salt must be sufficiently reducing such that the vast majority of the tritium is converted to H$_2$, with a HF to H$_2$ ratio less than 0.01. On the other hand, the potential must remain sufficiently oxidizing to prevent salt precipitation, resulting in a narrow operating window ($\Delta U\sim0.1V$ for Flibe) at reactor operating temperatures. However, H$_2$ is highly diffusive and must be continuously removed from the system and captured to minimize the potential for a significant radiological release [19].

The removal of tritium from salt is a coupled problem of redox chemistry and transport that requires understanding and accurate prediction of the $in-situ$ behavior of possible tritium species. Differences in diffusion and reaction rates can result in differential species removal rates. Depending
on the system design, this can change the relative quantities of the H oxidation states present in the salt, which can shift the redox potential and corrosivity [20][21]. The redox potential determines the equilibrium concentration of stable metal fluorides (impurities or fission products) in the melt, which can interact with the salt and produce unwanted changes in performance. Thus, the transport and chemical properties of tritium must be precisely quantified and understood. Yet, little reliable experimental data is available due to the costly handling of toxic salts and radioactive tritium. Thus, tritium control has been repeatedly emphasized as a bottleneck in the road to developing any reactor using lithium-based molten salts [22][23].

In this work, we examine the chemical behavior of tritium species in both prototypical salts Flibe and Flinak. First-principles simulation is used to interpret experimental results and predict salt properties, elucidating the chemical structure and transport properties required to predict tritium evolution in the system. This work establishes a link between tritium chemistry and transport behaviors over the thermodynamic conditions for a typical operating reactor. By comparing disparate experimental results with predictions from first principles, we highlight experimental methods and provide further guidance for measuring radioactive salts. Lastly, our validated calculations also generate useful engineering data that can be directly used in the design of tritium or salt handling systems.

2 Tritium structure and transport in molten salt

Since few experiments were performed and the redox chemistry in the system is usually not controlled, identifying the particular species of interest (HF or H2) remains difficult. For tritium transport properties, the reported values spread over orders of magnitude with great uncertainty [24][25][26][27][28][29]. The experimental uncertainty depends on the technique (capillary, membrane, pulsed-gradient nuclear magnetic resonance), but can generally be expected to be in ± 20%
range [30][31][32][33]. For structural analysis, X-ray and neutron diffraction patterns are used. In practice, these methods should be coupled to simulation and other experimental methods to fully resolve features of multi-component systems [34][35][36].

In this work, tritium local structure, chemistry and transport are investigated using ab initio simulation with realistic dynamics and thermochemistry [37][38]. Dilute tritium as $^3\text{H}^+$ and $^3\text{H}^0$ are separately introduced into the prototypical molten salts. The simulation and analysis protocols are described in detail in the methods section. In addition to tritium-in-salt systems, calculated properties of various fluoride salts including LiF, KF, LiF-KF, BeF$_2$, NaF, Flibe and Flinak are compared and supported by experimental data, increasing confidence in simulation data. These salts were chosen due to their chemical similarity with the prototypical salts of interest, availability of data, and relevance in fuel processing, spent fuel recycling, cooling advanced fission reactors, or as potential breeders in fusion devices [39][40][41][42]. The results of these supporting calculations are discussed in supplemental information.

3 Results

3.1 Structure and chemistry of tritium in fluoride salts

3.1.1 Radial coordination of fluorine in Fibe and Flinak

To examine the local structures of both possible tritium oxidation states (of $^3\text{H}^+$ and $^3\text{H}^0$), Figure 1 shows the local coordination of fluorine and the $\text{H-F}$ radial distribution functions in Flibe and Flinak. In Flibe, tritium as $^3\text{H}^+$ shows a distinct peak with a maximum at the radial distance of 0.9 Å, which is close to the radii of covalent bond at 0.88 Å [43]. In comparison, the $\text{H}^0$-$\text{F}$ peak for $^3\text{H}^0$ is wide and shallow with first peak maximum located at 2.7 Å, indicating limited coordination between $\text{H}^0$ and $\text{F}$. 
This suggests limited ionic dissolution of the $^{3}\text{H}^{0}$ in Flibe. The coordination number $N(r)$ of fluorine to tritium is calculated by the integral of the RDF, which is also shown in Figure 1. This further confirms the peak shown by the RDF, where a plateau can be seen for $^{3}\text{H}^{+}$ but not for $^{3}\text{H}^{0}$. Over the trajectory, the coordination number of fluorine to tritium at each time step was tallied based on the cutoff distance of the first minimum of the RDF. It was found that the $^{3}\text{H}^{+}$ was coordinated to two fluorine atoms for 61% of the simulation and one fluorine atom for 39% of the simulation.

For Flinak, H–F coordination is very similar to that of Flibe. The H–F RDF, where tritium has a $+1$ oxidation state shows a distinct peak at 1.1 Å, with a calculated coordination number of 1.83, which indicates a coordination of either 1 or 2 atoms. Coordination tallying shows that the tritium was coordinated to two fluorine atoms 95% of the time, and only one fluorine for 5% of the simulation. The coordination number and peak distances are summarized in Table 1.
Figure 1: Radial distribution functions and running coordination number of $^3\text{H}$–F at prototypical operating temperature of 973K in a Flibe and b Flinak. The running coordination number is calculated by integration of the RDF.

Table 1: First peak radius and coordination number of $^3\text{H}^0/\text{H}^+–\text{F}^-$ pairs in Flibe and flinak at 973K (design temperature for typical reactor). The coordination number is determined by integration of the first shell of the RDF. Numbers are excluded for $^3\text{H}^0$ due to lack of clear solvation shell.

| Salt  | Ion pair  | First Peak Radius (Å) | Coordination Number |
|-------|-----------|------------------------|---------------------|
| Flibe | $\text{H}^+–\text{F}^-$ | 0.9                    | 1.76                |
|       | $^3\text{H}^0–\text{F}^-$ | 2.7                    | -                   |
| Flinak| $\text{H}^+–\text{F}^-$ | 1.1                    | 1.85                |
|       | $^3\text{H}^0–\text{F}^-$ | 2.7                    | -                   |

3.1.2. Tritium coordination complexes and reactions in Flibe

While coordination counting and RDF analysis gives a general indication of the nearest neighbor structure $^3\text{H}^+$ and $^3\text{H}^0$, it does not provide more detailed information of chemical transformation and speciation. In order to understand the chemical reaction and time-dependent coordination in extended systems, a graph theoretical approach combined with a hidden Markov model is used to automatically detect the generation and destruction of new complexes along the trajectory [44][45].
The dissolution of $^3\text{H}^+$ is confirmed in Figure 2, which shows the interatomic distance between a single $^3\text{H}^+$ atom and different fluorine atoms in the mixture. $^3\text{H}^+$ becomes coordinated to fluorine with an average interatomic distance of 1 Å, and jumps between different fluorine atoms during the simulation. In addition, tritium can coordinate to two fluorine atoms simultaneously as shown between $t = 15 - 24$ ps (the overlapping time period on 1 and 2 in Figure 2a) with fluorine atoms ‘1’ and ‘2’ (see Figure 2b for the snapshots). In contrast, $^3\text{H}^0$ remains un-coordinated to fluorine and the interatomic distance is always greater than 1.5 Å. Thus, $^3\text{H}^+$ appears much more reactive in Flibe than $^3\text{H}^0$. This suggests that $^3\text{H}^+$ has a higher solubility than $^3\text{H}^0$ in Flibe, which agrees with the relative magnitudes of their Henry’s coefficients in literature [46][47].

We found $^3\text{H}^+$ exists in various chemical forms, including HF, HF$_2^-$, BeF$_4$HF$_2^-$, and Be$_2$F$_7$HF$_3^-$, in the fractions shown in Figure 3d. A snapshot of the simulation is shown in Figure 3a, numerical representation of molecules is shown in 3b, and an example reaction is shown in Figure 3c. Simple fluorides HF and HF$_2^-$ were the most common states with mean life-time $\tau = 4.4$ and 1.8 ps at 973K respectively, while tritium bound to BeF$_4^-$ ($\tau = 0.43$ ps) tetrahedral and tetrahedral polymer chains were found to exist less than 15% of the simulation time (60 ps). The “other” category in Figure 3d consists of rare (single-event) structures making up the remainder of the simulation, which includes free tritium ion or tritium complexes with larger BeF complexes such as Be$_3$F$_{10}$HF$_4^-$ ($\tau = 0.33$ ps) or B$_4$F$_{13}$HF$_5^-$($\tau = 0.097$ ps), which existed for less than 0.1% of the simulation. With increasing temperature, free tritium and other transition states become more common, occupying 5% of the simulation at 973K, and up to 20% of at 1373K. The average lifetime of H$^+$ complexes reduces with increasing temperature with $\tau = 1.4, 1.0$ and 0.8 ps for 973, 1173 and 1373K respectively. For $^3\text{H}^0$ in flibe, no reactions were found and tritium existed solely as a H$_2$. 

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Figure 2: a $^3\text{H}^+$ in flibe, interatomic distance between tritium and fluorine atoms in the solution. The hopping $\text{H}^+$ occurs in sequence 1-5 shown below. Step 1 to 2 clearly show the existence of the $^3\text{H}$ $\text{F}_2^-$ complex where the $^3\text{H}^+$ is bound to two fluorine atoms. b Visualization of tritium hopping between two fluorine atoms labelled ‘1’ and 2’. The simulation temperature is 973K.
Figure 3: a snapshot of HF in Flibe, b equivalent representations of Be$_2$F$_7$ corner-sharing tetrahedral as an adjacency matrix and graph of nodes and vertices used to find chemical structures in system, c relationship between chemical structures found across spatial and temporal dimensions to construct reaction coordinates, d fraction of each molecule at 973K, 1173K, and 1373K

Reactions with H$^+$ involving the most common complexes are shown in Table 2, all of which involve the combination with HF to an existing atom or molecule in the solution. The first reaction shows that the formation of the HF$_2^-$ complex from F$^-$ ion and HF combination with $\Delta E = -0.4$ eV calculated for the isolated molecules. For this reaction, the rate of association and dissociation of F$^-$
with HF increases with increasing temperature, likely dependent on the amount of free fluorine that is available from the surrounding mixture. The second reaction involves a HF molecule bonding to a \( \text{BeF}_4^- \) tetrahedral complex with \( \Delta E = -0.6 \text{ eV} \). Reaction two is more than twice as frequent at 973K than 1173K and 1373K, which corresponds to the availability of \( \text{BeF}_4\text{HF}^2^- \) at lower temperatures as shown in Figure 3d. The last reaction shows the bonding of an HF molecule to two corner-sharing \( \text{BeF}_4^- \) tetrahedral complexes with \( \Delta E = -0.6 \text{ eV} \). The ‘other’ reactions all involve less common species, such as transition complexes swapping \( \text{F}^- \) ions with solution, or HF breaking and joining with larger Beryllium complexes: \( \text{Be}_3\text{F}_{10}\text{HF}^4^- \leftrightarrow \text{BeF}_3^- + \text{Be}_2\text{F}_7\text{HF}^3^- \). The frequency of these reactions increases with increasing temperature due to the increase in transient high-energy structures that are discovered at higher temperatures.

**Table 2:** Tritium \((^3\text{H}^+)\) reactions in Flibe found during simulations at 973, 1173 and 1373K.

| Reaction | \( T=973\text{K} \) | \( T=1173\text{K} \) | \( T=1373\text{K} \) |
|----------|-----------------|-----------------|-----------------|
| 1 F + HF\(\leftrightarrow\)HF\(_2^-\) | 22 | 32 | 35 |
| 2 \( \text{BeF}_4^2^- + \text{HF} \leftrightarrow \text{BeF}_4\text{HF}^2^- \) | 54 | 16 | 20 |
| 3 \( \text{Be}_2\text{F}_7^- + \text{HF} \leftrightarrow \text{Be}_2\text{F}_7\text{HF}^- \) | 8 | 18 | 3 |
| Other | 50 | 59 | 166 |

This analysis suggests high \(^3\text{H}^+\) reactivity to fluorine and beryllium mixture in Flibe, which are in agreement with the RDFs analysis and further confirm that solvation of \(^3\text{H}^+\) is significantly stronger than that of \(^2\text{H}^0\).
3.1.3. Tritium coordination complexes and reactions in Flinak

Examination of tritium coordination in Flinak reveals that $^3\text{H}^+$ is coordinated to two fluorine atoms for most of the simulation. At 973K, the tritium remains bonded with the same fluorine atoms ($|d_{\text{H-F}}| = 1.18\text{Å}$) for the simulation interacting with ions as $\text{HF}_2^-$. At the higher temperatures, the $\text{HF}_2^-$ is able to exchange $\text{F}^-$ with the solution and the tritium becomes more dissociative. The most common states for $^3\text{H}^+$ are shown in Figure 4, of which the most common structure is $\text{HF}^2^- (\tau = 12 \text{ ps at } 973\text{K})$ which existed for 80-90% of the 60-ps simulation, followed by $\text{NaF}_4\text{HF}^3^- (\tau = 0.14 \text{ ps})$ and $\text{NaF}_3\text{HF}^4^- (\tau = 0.25 \text{ ps})$, which were found to be present for 1.5 – 5% of the simulation. The ‘other’ category of the simulation again includes rare atomic structures such as $\text{HF} (\tau = 0.16 \text{ ps}), \text{NaF}_3\text{HF}^2^- (\tau = 0.09 \text{ ps})$ appearing at 1373K.

Figure 4: a Tritium molecules in Flinak, b Fraction of each molecule at 973K, 1173K, and 1373K.

In Flinak, all the cations are monovalent and form fewer complex molecules, in contrast to Flibe where longer chains of Be–F complexes are found. Li or K do not form detectable reaction products, indicating free lithium and potassium ions in solution. Most sodium atoms in the simulation were also freely dissociated; only ~11% of the Na found in a polyhedral configuration (3% as NaF$_4$, 8%
as NaF$_3$). Further, Na complexes usually have lifetimes on the order of 10$^2$ fs and readily react or exchange with fluorine in the solution. As a result, relatively few H$^+$ reactions were found in the solution. A handful of reactions found included HF$_2^-$ combination reactions with NaF complexes such as: HF$_2^-$ + NaF$_4^{3-}$ $\leftrightarrow$ NaF$_5$HF$^4^-$ ($\Delta$E = $-0.5$ eV), and NaF$_5$HF$^4^-$ + F$^-$ $\leftrightarrow$HF$_2^-$ +NaF$_3^{3-}$ ($\Delta$E = $-0.1$ eV). At the higher temperatures of 1173K and 1373K, some dissociative behavior was observed for HF$_2^-$ with the fluorine ejection reaction HF$_2^-$ $\leftrightarrow$HF + F$^-$ ($\Delta$E = 0.5 eV) observed 4 times.

In Flinak, the behavior of $^3$H$^0$ is similar to that in Flibe, where tritium exists purely as H$_2$ with $|d_{\text{H-H}}| = 0.8$ Å at 973K. This again agrees with the result of the radial distribution function in Figure 1, which shows weak solvation of hydrogen with fluorine. Thus, in both clean Flibe and Flinak, $^3$H$^0$ shows little chemical interaction with surrounding ions compared to $^3$H$^+$.

3.2 Tritium diffusivity in FliBe and FLiNaK

In this section, the calculation of diffusivity and activation energy of hydrogen is discussed for clean Flibe and Flinak and compared to existing data. It should be noted that the form of tritium measured in experiments is not explicitly known because metallic impurities and corroding materials can form halides in the salt and change the chemical form of tritium being measured as described in Section 1. In this study, the isotopic effect of hydrogen is expected to be small, especially relative to the differences between experiments [48][49].

3.2.1 Tritium diffusivity in FliBe

The diffusivity and activation energy of hydrogen isotopes has been measured by four studies over the temperature range of 1020 – 1325K [25][24][26][27]. Figure 5 compares the results of the different experiments against the simulation of tritium as $^3$H$^+$ and $^3$H$^0$. 
The calculated diffusivity for $^{3}\text{H}^{0}$ was found to be on average 3-4 times larger than that of $^{3}\text{H}^{+}$. Such a large difference in diffusivity is related to the coordination of $^{3}\text{H}^{+}$ with beryllium fluoride complexes and fluorine in the mixture. The calculated diffusivity and activation energies are shown in Table 3. The diffusion equation for two oxidation states are expressed:

$$D_{^{3}\text{H}^{0},\text{Flibe}}[\text{m}^2\text{s}^{-1}] = 9.349 \times 10^{-7} \exp \left( - \frac{40.0 [\text{kJmol}^{-1}]}{RT} \right)$$

(1)

$$D_{^{3}\text{H}^{+},\text{Flibe}}[\text{m}^2\text{s}^{-1}] = 2.758 \times 10^{-7} \exp \left( - \frac{36.0 [\text{kJmol}^{-1}]}{RT} \right)$$

(2)

The calculated activation energies for $^{3}\text{H}^{0}$ and $^{3}\text{H}^{+}$ are similar, 40.0 ± 3.0 kJ/mol and 36.0 ± 2.0 kJ/mol respectively. Compared to the experimental data, the simulation results are within error bounds of Calderoni’s and Oishi’s experiments. In Oishi’s experiment [25], tritium is generated as $^{3}\text{H}^{+}$ from salt irradiation. However, some of the tritium is likely to chemically react with the Ni container to generate $^{3}\text{H}_2$. In Calderoni’s experiment [24], hydrogen purge gas is used, which likely isotopically exchanges with $^{3}\text{HF}$ to form $^{3}\text{H}^{1}\text{H}$ in the solution. Further, both experiments purified the salt by hydrofluorination and thus may contain some proportion of $^{1}\text{H}$ molecules which could react or exchange with $^{3}\text{HF}$ or $^{3}\text{H}_2$. Thus, in both experiments, the diffusivity measurement likely corresponds to a combination of tritium species and oxidation states. The activation energy calculated using Oishi’s data was 36.0 ± 6.0 kJ/mol, and the activation energy from Calderoni was found to be 42.0 ± 7.0 kJ/mol, which are similar to the computational values.
Figure 5: Experiments versus simulation. Calderoni used tritium $^3\text{H}$ gas diffusing across a 1-D nickel membrane, Oishi used $^3\text{H}$ created by salt irradiation and measured diffusion in a capillary, Anderl used $^2\text{H}$ diffusion in a cylindrical cell, and Nakamura used $^1\text{H}$ in a cylindrical cell. The shaded region represents 95% confidence interval of regression [25][24][26][27].

Table 3: Calculated diffusivities of tritium as $^3\text{H}^+$ and $^3\text{H}^0$ in Flibe

| Temperature (K) | $^3\text{H}^+$ diffusivity * 1E9 (m$^2$/s) | $^3\text{H}^0$ diffusivity * 1E9 (m$^2$/s) |
|-----------------|---------------------------------|---------------------------------|
| 973             | 3.0 ± 0.5                       | 6.3 ± 1.4                       |
| 1173            | 7.0 ± 1.3                       | 16.3 ± 3.3                      |
| 1373            | 11.1 ± 1.6                      | 27.0 ± 4.1                      |

In the other two studies, data collection was limited (2-3 experimental measurements), and data significantly diverged from simulation and previous experiments. Both used diffusion in a similar cylindrical diffusion cell. In Anderl’s experiment [26], diffusivity measured was 0.8×10^{-5} cm$^2$/s, which is 80% lower than computed $^3\text{H}^0$ diffusivity and 40% lower than $^3\text{H}^+$ calculated from Equation (1) and (2). In Anderl’s experiment, impurity analysis found 600 ppm of oxygen impurity in the salt before the start of the experiment. This combined with any potential oxygen ingress could cause reactions with...
HF via: BeO + 2HF → BeF₂ + H₂O. In this case, the measured diffusivity could actually be that of H₂O or other intermediate reaction complexes. Further, their analytical model used diverged from their experimental data over time. This suggests a systematic error in the transport model, possibly due to increasing air ingress or other interfacial effects [26]. Similarly, Nakamura’s experiment under-predicted by the same order of magnitude at 823 K [27]. The experimental activation energy was also lower than the calculated values at 25.2 ± 8 kJ/mol. In Nakamura’s study, the lower diffusivities and activation energies could be caused by potential impurities (not measured) or temperature gradients in the experimental cell.

While previous studies have found that impurities can significantly increase in corrosion and change the thermochemical properties of salt, the specific impact of different impurities on tritium is not well understood [8][9]. Here, additional simulations were performed for tritium and Flibe in the presence of a single unit of Cr (dominant corrosion product) and H₂O (atmospheric moisture) at 973K. In these cases, tritium diffusivity decreased by 25% and 15% respectively. From structure analysis, tritium was found to coordinate with the impurities (Cr-³H and ³H-O bonding), which likely resulted in the observed differences in diffusivity relative to pure Flibe. The structures discovered can be found in the supplementary information in Figure S7. Similarly, it was found that the introduction of corrosion impurities (CrF, HF) can alter the diffusivities and activation energies of Li and F ions in Flibe shown in Figure S6. These results support the idea that impurity effects can impact experimental results summarized in Figure 5 and provides further evidence that impurities can significantly impact chemical and transport properties. However, many more atmospheric and fission-generated impurities can exist simultaneously, which can have unpredictable effects in real systems. As such, the role of impurities in...
a variety of chemical forms, oxidation states, and conditions warrants a more detailed investigation in future studies.

3.2.2 Tritium diffusivity in Flinak

The diffusivity of hydrogen isotopes in Flinak has been measured by only three experimental studies, which all used $^1$H as shown in Figure 6 [28][29][27]. Similar to the relative behavior of tritium in Flibe, $^3$H$^0$ diffuses faster than $^3$H$^+$. The average diffusivity of $^3$H$^0$ is 4× larger than that of $^3$H$^+$ across the temperature range from 973 K to 1373 K (Table 4). The diffusion coefficients are expressed:

\[
D_{^3\text{H}^0,\text{Flinak}}[\text{m}^2\text{s}^{-1}] = 4.316 \times 10^{-7} \exp\left(-\frac{29.0 \ [\text{kJmol}^{-1}]}{RT}\right)
\]

(3)

\[
D_{^3\text{H}^+,\text{Flinak}}[\text{m}^2\text{s}^{-1}] = 1.156 \times 10^{-7} \exp\left(-\frac{29.0 \ [\text{kJmol}^{-1}]}{RT}\right)
\]

(4)

The activation energies of both oxidation states are similar at $29.0 \pm 6.4 \text{ kJ/mol}$ for $^3$H$^0$ and $29.0 \pm 9 \text{ kJ/mol}$ for $^3$H$^+$ in Flinak. From analysis of chemical structure, the lower diffusivities of $^3$H$^+$ can be attributed to the fact that the molecule exists as a larger and more chemically reactive molecule $\text{HF}_2^-$ in the melt, whereas $^3$H$^0$ exits as H$_2$. The lower activation energies of tritium in Flinak compared to Flibe indicate a lower diffusion barrier. This can be rationalized in terms of chemical structures in both salts; the formation of $\text{BeF}_4^{2-}$ chains in Flibe obstructs transport while relatively free ions dominate in the Flinak solution. Like Flibe, the redox condition in Flinak can be either reducing or oxidizing depending on the impurities in the salt.
Figure 6: Comparison of hydrogen diffusivity between ab initio simulations and three experiments. Experiment by Zeng and Fukada diffuse H$_2$ across a 1-D nickel membrane, while experiment by Nakamura was done by radial diffusion across a cylindrical Monel window. The highlighted region represents the 95% confidence interval from regression of the collected data [27][28][29].

Fukada suggested that their results measured H$^0$, which showed the most similarity to the calculated diffusivity of $^3$H$^0$ compared to other studies. In this experiment, tests were performed to ensure low corrosion of nickel due to contact with Flinak. Further, both pH and mass spectroscopy were performed during the diffusion measurement to confirm H$_2$ measurement was up to a sensitivity of 1 ppm and HF up to sensitivity of 1 ppb. Here, the simulations again confirm the importance of accurately confirming the redox and impurity state. The activation energy calculated from their data from 800K to 1000K was 43.0 ± 4.7 kJ/mol, which is higher than the simulated values. This is likely due to the higher temperatures used in simulation. Fukada found that, the activation energy for diffusion increased at lower temperatures due to increased mass transfer resistance at interfaces caused by increased H$^+$ interaction. Thus, these results show good agreement with our simulations in general.

Table 4: AIMD diffusivities of tritium as $^3$H$^+$ and $^3$H$^0$ in Flinak
In contrast, corrosion impurities and chemical species were not measured explicitly in the other two studies. In both studies, this is combined with a limited number of experimental data points, yielding high uncertainty in the overall result. The activation energy calculated by Nakamura was found to be near-zero to slightly negative -5.4 ± 5.7 kJ/mol, which has not been observed in any other species transport in molten salts [30]. Here, we note that Nakamura’s Flinak study uses the same experimental procedure as their Flibe study discussed in Section 3.2.1, both of which show significant deviations from simulations in this work and other experiments in the literature. This suggests a systematic error in the study, possibly caused by the measurement protocol (cylindrical diffusion with analytical model), or the use of hydrogen interacting materials (Monel). This effect, along with impurity interaction as examined for Flibe in Section 3.2.1, should be explored more thoroughly since the diffusivity and activation energies differ dramatically from other experimental data and these simulations.

### 3.3 Implications of coupled hydrogen diffusion and chemistry in molten salt

In this work, tritium chemistry and transport are examined for the two possible tritium oxidation states H⁰ and H⁺ in prototypical salts Flibe and Flinak. Accurate prediction of these properties is critical for the design of salt systems that can contain hydrogen from moisture ingress or generated by irradiation. In many systems, the tritium transport in salt could limit overall transport due to relatively slow diffusion through salt, particularly as H⁺ ion. Further, quantifying large
differences in chemistry and transport behavior of different chemical forms ($D_{H^0}:D_{H^+} \approx 2-5$) is important in understanding and controlling the redox condition, and consequently, corrosiveness of the salt. Conventionally, the differences between the diffusion of $H^0$ and $H^+$ in molten salt has been ignored due to a lack of information. In some cases, it has even been assumed that $D_{H^+} > D_{H^0}$, which could cause significant error in predicting transport behavior [50][20]. From this work, it is clear that experiments that controlled for speciation, impurities, and corrosion produced more reliable data than those that did not, which was supported by simulation results. Further, the simulations provide insights that allowed understanding of transport behavior at the level of local atomic structure, which would otherwise be difficult to infer from experimental data alone.

4 Conclusions

Through extensive first-principles molecular dynamics simulations, we discovered that hydrogen transport in molten fluorides depends on its oxidation state and the salt’s redox condition. We examined the bonding and connectivity of $^3H^+$ and $^3H^0$ and established the link between chemistry and transport properties in prototype salts Flibe and Flinak. In addition, we accurately predicted the local structure ($\pm 0.1$ Å peak distance, and $\pm 0.4$ coordination) and ionic diffusivities (within experimental uncertainty, $\pm 20\%$) of various binary, ternary and quaternary molten salt fluorides. Chemical analysis was performed using a combination of local radial structure, and an automated search of molecular graphs to monitor temporal changes in extended chemical structures.

Chemical-structural analyses suggest that, in fluoride salt, $^3H^+$ shows soluble and dissociative behaviors in both Flibe and Flinak. Specifically, $^3H^+$ coordinates with $BeF_2^-\text{tetrahedral corner-sharing polymer-like structures in Flibe, while, in Flinak,}^3H^+$ exists as $HF_2^-$ with some association to
NaF polyedra. In contrast, $^3\text{H}^0$ remained bound as a gaseous dimer $\text{H}_2$ in both Flibe and Flinak. As a result, the diffusivity of $^3\text{H}^0$ is 3-4× and up to 5× higher than that of $^3\text{H}^+$ in Flibe and Flinak, respectively. Further, the diffusion activation energies in Flibe (40.0 ± 3.0 kJ/mol for $^3\text{H}^0$ and 36.0 ± 2.0 kJ/mol $^3\text{H}^+$) are higher than those in Flinak (29.0 ± 6.4 kJ/mol for $^3\text{H}^0$ and 29.0 ± 9 kJ/mol for $^3\text{H}^+$) due to the formation of BeF networks that lower overall ionic transport in Flibe, in comparison to Flinak where ions are predominately free. In both salts, the $^3\text{H}^+$ activation energy is similar to $^3\text{H}^0$, showing fairly weak association with similar characteristic to hydrogen bonding between hydrogen and fluorine atoms.

In interpreting the limited experimental results with wide discrepancies spanning more than an order of magnitude, our ab initio simulations provide a deeper understanding of experimental sources of error like impurity concentration, surface effects, and corrosion. Furthermore, we provide atomistic level insight into the interplay among oxidation states, structures and transport properties of tritium in both Flibe and Flinak, as well as useful engineering data that is difficult to obtain experimentally. The relative differences between $\text{H}^0$ and $\text{H}^+$ can greatly impact the design of impurity removal and corrosion control systems in both nuclear and non-nuclear salt-based systems. In advanced nuclear reactors, diffusive radiological release and corrosion are two of the most prominent challenges that are tightly coupled through tritium transport and chemistry. This work elucidates hydrogen behavior that must be accounted for in future experiments and modeling of molten salts.
5 Methods

5.1 Materials and salt systems

A range of fluoride systems were simulated and compared against experimental structure and transport data over a range of temperatures from 775 – 1373K. These systems include LiF, KF, NaF, BeF₂, LiF-KF, LiF-BeF₂ and LiF-NaF-KF, which can be found in the supplemental information. Tritium as \( ^3\text{H}^0 \) and \( ^3\text{H}^+ \) were added as a single HF and H₂ as they would be found in prototypical salts Flibe (66.6%LiF-33.3%BeF₂) and Flinak (46.5%Li-11.6%NaF-41.9%KF). The Flibe consisted of 10 Be, 40 F, and 20 Li and Flinak consisted of 20 Li, 5 Na, 18 K, and 43 F to make 46.5%Li-11.6%NaF-41.9%KF.

In each system, the cell size was chosen to match the experimental density of the salt. For systems where accurate density is not known, it can be estimated by running a series of simulations to fit an equation of state, or by running the isobaric-isothermal ensemble (NpT) until equilibrium is reached. The relatively small system sizes are chosen for computational efficiency. While periodic effects might be expected for smaller system sizes, it has been shown by simulating larger cells of up to 200 atoms that properties like diffusion and local structure are generally converged on the smaller system sizes [37][37].

5.2 First-principles molecular dynamics simulations

In all of the salts, the system was initialized by randomizing the positions using Packmol software [51]. The system was equilibrated under the canonical ensemble (NVT) for at least 10 picoseconds at least 200 K above the melting point. The production runs lasted for at least 60 picoseconds sampled at 1fs timestep. The temperature was controlled with a Nosé-Hoover thermostat using a Nosé mass corresponding to a period of 40 fs. Born-Oppenheimer ab initio molecular dynamics (AIMD) was performed with the Vienna Ab-initio Simulation Package [52][53]. Periodic boundary conditions were used in all directions. The AIMD calculations were performed with density functional theory (DFT) using a generalized gradient approximation (GGA) functional for electron exchange and correlation energy. The projector augmented wave (PAW) Perdew-Burke-Ernzerhof (PBE) functionals used were Liₘₗ, Be, F, Naₚᵥ, Kₘₗ and H.
energy cutoff of 600 eV was used for plane wave expansion, and the Brillouin zone was sampled at the \( \Gamma \)-point only to improve computational speed. The parameters chosen have been shown to yield good convergence within 2 meV/atom [54].

5.3 Atomic coordination and complexation analysis

Chemical analysis was performed by two methods. The first is simple and involves the examination of coordination based on the radial distribution function (RDF). The coordination of a central atom is found by taking the sum of the number of neighbor atoms within a distance cutoff. The cutoff is specified using the first minimum of the RDF of each species pair. The coordination numbers of each element with respect to the others are tallied to produce a time-averaged distribution. The averaged coordination number over the trajectory is determined by the integration of the RDF \( g(r) \) [55]:

\[
N_{A-B} = 4\pi \rho_B \int_0^{r_m} r^2 g_{A-B}(r) dr
\]

(5)

Where, \( N_{A-B} \) is the nearest neighbor coordination number, \( \rho_B \) is the number density of species B, and \( r_m \) is the radius of the first minimum of \( g(r) \). By performing the search on coordination distribution, immediate local structures are easily found.

The second method allows for the detection of extended molecular structures and reactions by using graph-theory based searching algorithms followed by statistical filtering for noise removal. The method follows that of Martinez [56][45], which has previously been used to study reactions and transport in organic systems and surfaces [57][58][44][59]. At each step in the trajectory, the system is represented by an atomic graph with nodes \( N \) and edges \( E \). The nodes represent individual atoms, while the edges represent bonds between atoms, defining the graph \( G_t \) as below:

\[
G_t = (N:\{A_1,...,A_n\}, E:\{R_{ij} \leq R_{ij}^C\})
\]

(6)
where $R_{ij}$ is the Euclidean distance between atom $i$ and $j$, $A_1...A_n$ contain information on the atom’s elemental species and unique index in the simulation. $R_{ij}^C$ is the radial cutoff distance to register atoms as being bonded, which in this case is defined based on the atomic species of $i$ and $j$. In previous work, the bond length was estimated by the sum of covalent radii [43]. However, this can be significantly different than the actual length of associated atoms in an ionic liquid. Thus, the cutoffs are estimated from the bond lengths found in the simulation RDFs: $R_{ij}^C = 1.4 \cdot \bar{R}_{ij}$ where $\bar{R}_{ij}$ is the average bond length determined from the radial distribution function, and a factor of 1.4 is applied to encapsulate thermal noise due to vibrations at high temperature. At each time step, the overall graph $G_t$ can be separated into its component connected subgraphs $g_m$, which represent individual molecules. The subgraphs are found using the breadth-first search algorithm [60].

For each molecular subgraph found in the simulation, a binary time series $E^m(t)$ is constructed valued at 1 or 0 is constructed to indicate whether the subgraph exists (value of 1) at each time step in the simulation. The observed signal $E$, is modeled using a two-state Hidden Markov Model (HMM) in which there exists an underlying lower-frequency signal $X$, representing the true signal. The HMM is defined by the joint probability [61]:

$$P(X,E) = P(X_0) \prod_{i=1}^{t} P(X_i | X_{i-1}) P(E_i | X_i)$$  \hspace{1cm} (7)$$

where the output probability matrix containing $P(E_i | X_i)$ and the transition probability matrix containing $P(X_i | X_{i-1})$ are parameterized:

$$O = \begin{pmatrix} 0.6 & 0.4 \\ 0.4 & 0.6 \end{pmatrix} ; \quad T = \begin{pmatrix} 1 - t_p & t_p \\ t_p & 1 - t_p \end{pmatrix}$$  \hspace{1cm} (8)$$
The transition probability of switching states, $t_p$, was set between $10^{-6} - 10^{-7}$, which is markedly low to provide a stronger noise filter that removes false transitions in the observed signal. This is necessary due to the high-temperature liquid state causing high-frequency fluctuations in the system. The Viterbi algorithm is used to find the likely sequence $X$ that produced observation $E$.

With the filtered sequences $X^m$ for each molecule, chemical reactions are then found. The generation of a new product is characterized by a $0 \rightarrow 1$ transition in the sequence occurring at time $\tau_p$, and the destruction of a reactant is characterized by a $1 \rightarrow 0$ transition at $\tau_r$. At each product time, the nearest reactants and products in time are located and a chemical balance is performed, checking for stoichiometric conservation among the reactants and products. If a reaction is not found, the search window for reactants and products is iteratively expanded, until chemical balance can be achieved or a maximum search window $\Delta \tau = 150$ fs is reached. If no atom-conserving reaction can be found for a generated product, it is disregarded as unfiltered noise. The reaction energies are determined by performing geometry optimized DFT calculations on the reactants and products extracted from the trajectory.

### 5.4 Calculation of diffusivity

The diffusion coefficient is taken as self-diffusivity at the dilute limit. This applies to the single hydrogen atom in the molten salt simulation cells, and to experiments where tritium concentrations exist at the ppm level [46][47]. The diffusivity is calculated from the slope of the mean squared displacement as a function of time by the Einstein relationship:

$$D = \frac{1}{6} \lim_{t \rightarrow \infty} \frac{d}{dt}(\text{MSD})$$

(10)
where the slope is determined for and averaged over subsets $n_t$ of the total trajectory, and over all the
atoms of the same elemental type:

$$\text{MSD} = \frac{1}{N} \sum_{j=1}^{n_t} \sum_{i=1}^{N} (r_i(t_j + dt) - r_i(t_j))^2$$

(11)

where $r_i(t)$ is the coordinates of atomic $i$ at time $t$, and $dt$ is the length of time spanned by each subset
in time. The total trajectory spanned more than 60,000 time steps (60 ps), of which more than 15 equal-
sized sub-trajectories were sampled. Sufficient spacing was used between time origins to eliminate
correlation between diffusion evaluations. The standard error and confidence intervals were
determined using the block-averaging method [62].

**Acknowledgment.** SL acknowledges funding support from the National Science and Engineering
Research Council of Canada, and the Shanghai Institute of Applied Physics. QJL and JL acknowledge
support by the Department of Energy, Office of Nuclear Energy, Nuclear Energy University Program
(NEUP) under Award Number DE-NE0008751.

**Author Contributions.** S.L, C.F., R.B, and J.L conceived and guided the overall study. S.L and QJ
performed data generation and analysis. S.L and J.M. developed the graph-theoretic code for chemical
analysis of extended structures. All authors contributed to the preparation of the manuscript.

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