



# Electrochemical behavior of hexafluoronioabate, heptafluorotungstate, and oxotetrafluorovanadate anions in *N*-butyl-*N*-methylpyrrolidinium bis(trifluoromethylsulfonyl)amide room temperature ionic liquid

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## ARTICLE INFO

### Article history:

Received 22 December 2010  
Received in revised form 17 February 2011  
Accepted 18 February 2011  
Available online 24 February 2011

Dedicated to Prof. Alain Tressaud on the occasion of receiving the ACS award for Creative Work in Fluorine Chemistry.

### Keywords:

Ionic liquids  
NbF<sub>6</sub><sup>-</sup>  
WF<sub>7</sub><sup>-</sup>  
VOF<sub>4</sub><sup>-</sup>  
Diffusion coefficient  
Stokes radius

## ABSTRACT

Electrochemical behavior of hexafluoronioabate (Nb(V)F<sub>6</sub><sup>-</sup>), heptafluorotungstate (W(VI)F<sub>7</sub><sup>-</sup>), and oxotetrafluorovanadate (V(V)OF<sub>4</sub><sup>-</sup>) anions has been investigated in *N*-butyl-*N*-methylpyrrolidinium bis(trifluoromethylsulfonyl)amide (BMPyrTFSA) ionic liquid at 298 K by means of cyclic voltammetry and chronoamperometry. Cyclic voltammograms at a Pt electrode showed that Nb(V)F<sub>6</sub><sup>-</sup> anion is reduced to Nb(IV)F<sub>6</sub><sup>2-</sup> by a one-electron reversible reaction. Electrochemical reductions of W(VI)F<sub>7</sub><sup>-</sup> and V(V)OF<sub>4</sub><sup>-</sup> anions at a Pt electrode are quasi-reversible and irreversible reactions, respectively, according to cyclic voltammetry. The diffusion coefficients of Nb(V)F<sub>6</sub><sup>-</sup>, W(VI)F<sub>7</sub><sup>-</sup> and V(V)OF<sub>4</sub><sup>-</sup> determined by chronoamperometry are  $1.34 \times 10^{-7}$ ,  $7.45 \times 10^{-8}$  and  $2.49 \times 10^{-7}$  cm<sup>2</sup> s<sup>-1</sup>, respectively. The Stokes radii of Nb(V)F<sub>6</sub><sup>-</sup>, W(VI)F<sub>7</sub><sup>-</sup>, and V(V)OF<sub>4</sub><sup>-</sup> in BMPyrTFSA have been calculated to be 0.23, 0.38, and 0.12 nm, from the diffusion coefficients and viscosities obtained.

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## 1. Introduction

Electrochemistry of transition metal species in ionic liquids (ILs) has been widely investigated due to the wider electrochemical windows of ILs than those of aqueous systems in addition to their unique properties such as low melting points, nonflammability, low vapor pressure, and wide temperature range of liquid phase [1–9]. The electrochemical behavior of Fe(II) [10,11], Co(II) [12], Ti(IV) [2,13], V(III), V(IV), V(V) [14], Mg(II), U(IV), Ta(V), Mn(II), Ru(III), and Rh(III) [13] in ILs was reported in view of the application for metal electrodeposition. Redox behavior of some transition metals, such as Fe(II), Sm(III), Eu(III), and Yb(III) in *N*-butyl-*N*-methylpyrrolidinium bis(trifluoromethylsulfonyl)amide (BMPyrTFSA) was investigated for redox flow batteries using ILs [15].

A series of *N*-alkyl-*N*-methylpyrrolidinium salts based on the fluorocomplex anions (BF<sub>4</sub><sup>-</sup>, PF<sub>6</sub><sup>-</sup>, NbF<sub>6</sub><sup>-</sup>, TaF<sub>6</sub><sup>-</sup>, and WF<sub>7</sub><sup>-</sup>) have been prepared by fluoroacid-base reactions between fluorohydrogenate ILs and binary fluoroacid (AF<sub>*m*</sub>), and have been

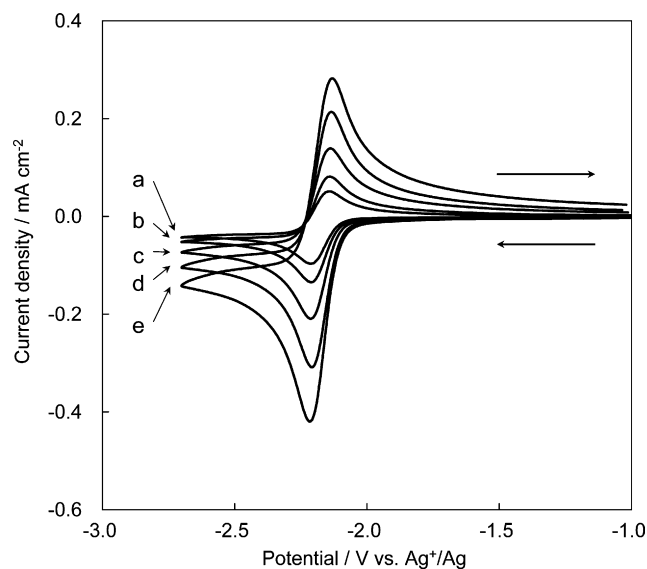
characterized by spectroscopic, physical, and chemical methods [16]. Although electrochemical data are available for some chloro- and bromo-metallate anions [17–23], there are not many reports on electrochemical data for fluorometallate and oxofluorometallate anions and, to our knowledge, no reports are available for the electrochemical behavior of Nb(V)F<sub>6</sub><sup>-</sup>, W(VI)F<sub>7</sub><sup>-</sup>, and V(V)OF<sub>4</sub><sup>-</sup> at 298 K. In this paper, the electrochemical behavior of Nb(V)F<sub>6</sub><sup>-</sup>, W(VI)F<sub>7</sub><sup>-</sup>, and V(V)OF<sub>4</sub><sup>-</sup> in BMPyrTFSA at 298 K is discussed in detail, where BMPyrTFSA was chosen as a medium because of its high electrochemical stability and easy handling.

## 2. Results and discussion

### 2.1. Electrochemical behavior of Nb(V)F<sub>6</sub><sup>-</sup>

Fig. 1 shows the cyclic voltammograms at a Pt electrode in BMPyrTFSA containing 29.2 mM BMPyrNbF<sub>6</sub>. Only one cathodic wave is observed around -2.2 V vs. Ag<sup>+</sup>/Ag during the cathodic scan. The cathodic and anodic peak current densities (*i*<sub>p</sub><sup>c</sup> and *i*<sub>p</sub><sup>a</sup>) increase with increase in scan rate, and their peak potentials (*E*<sub>p</sub><sup>c</sup>) are essentially unchanged, indicating a high reversibility of this electrochemical reaction. In the case of a reversible reaction, the

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**Fig. 1.** Cyclic voltammograms of a Pt electrode in BMPyrTFSA containing 29.2 mM of BMPyrNbF<sub>6</sub> at 298 K. Scan rate: (a) 1 mV s<sup>-1</sup>, (b) 2 mV s<sup>-1</sup>, (c) 5 mV s<sup>-1</sup>, (d) 10 mV s<sup>-1</sup>, and (e) 20 mV s<sup>-1</sup>.

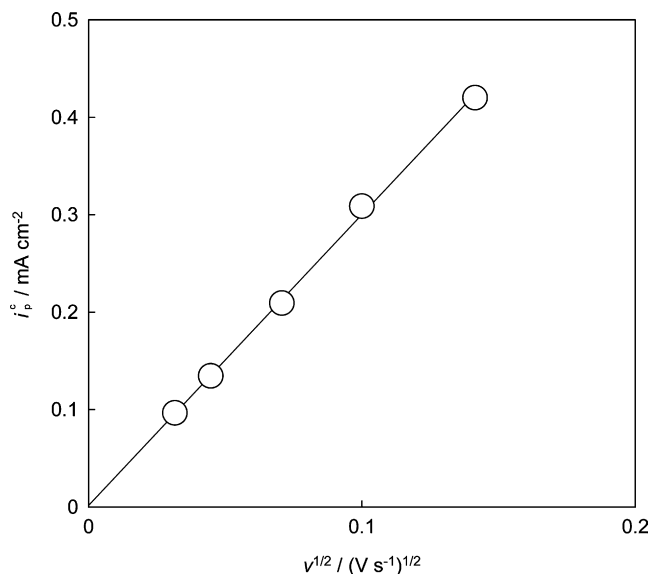
following relation holds [24]:

$$|E_p^c - E_{p/2}^c| = \frac{0.0565}{n} \quad (1)$$

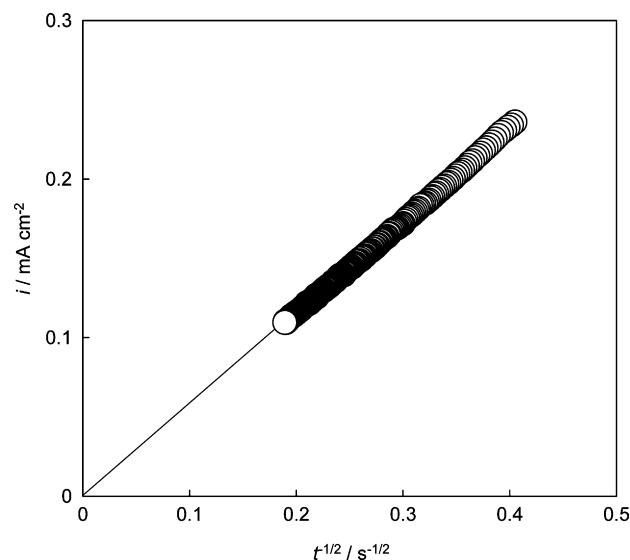
where  $E_{p/2}^c$  is the half-peak potential and  $n$  is the number of electrons. The value of  $n$  is calculated to be around 0.8, suggesting the number of electrons for this reaction is one. Thus, the present electrode reaction of NbF<sub>6</sub><sup>-</sup> in BMPyrTFSA is described as follows:



Table S1 lists the data of cyclic voltammogram obtained for the reduction of NbF<sub>6</sub><sup>-</sup>. As shown in Fig. 2, the linear dependence of the cathodic peak current density ( $i_p^c$ ) and square root of scan rate ( $\nu^{1/2}$ ) also confirms the electrochemical reduction of NbF<sub>6</sub><sup>-</sup> is a reversible reaction. The diffusion coefficient of NbF<sub>6</sub><sup>-</sup> is calculated



**Fig. 2.** The  $\nu^{1/2} - i_p^c$  plots for the reduction of NbF<sub>6</sub><sup>-</sup> in BMPyrTFSA containing 29.2 mM of BMPyrNbF<sub>6</sub>.



**Fig. 3.** The  $t^{-1/2} - i$  plots for the reduction of NbF<sub>6</sub><sup>-</sup> in BMPyrTFSA containing 29.2 mM of BMPyrNbF<sub>6</sub>.

from the slope of Fig. 2 using Eq. (3) [24]:

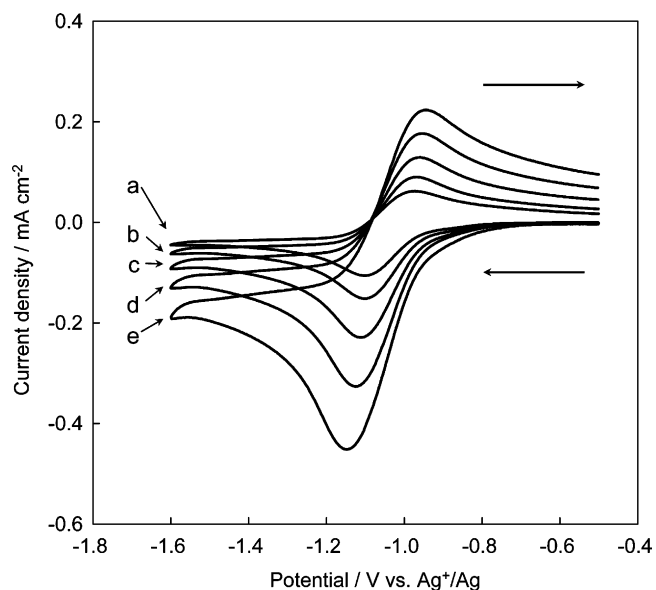
$$i_p^c = (2.69 \times 10^5) n^{3/2} D^{1/2} C \nu^{1/2} \quad (3)$$

where  $C$  is the concentration of NbF<sub>6</sub><sup>-</sup> and  $D$  is the diffusion coefficient. From this equation,  $D$  was calculated to be  $1.46 \times 10^{-7}$  cm<sup>2</sup> s<sup>-1</sup>.

The electrochemical behavior of NbF<sub>6</sub><sup>-</sup> was also investigated by chronoamperometry. Fig. 3 shows the Cottrell plot for the reduction reaction from NbF<sub>6</sub><sup>-</sup> to NbF<sub>6</sub><sup>2-</sup> at a Pt electrode, where the potential was stepped from -0.6 to -2.3 V vs. Ag<sup>+</sup>/Ag. The Cottrell equation describing the current density ( $i$ ) against time ( $t$ ) for the reduction of electroactive species is given by Eq. (4) [24]:

$$i = n F C D^{1/2} \pi^{-1/2} t^{-1/2} \quad (4)$$

The obtained straight line passing through the origin in Fig. 3 indicates the validity of a simple diffusion controlled reduction,



**Fig. 4.** Cyclic voltammograms of a Pt electrode in BMPyrTFSA containing 61.8 mM of BMPyrWF<sub>7</sub> at 298 K. Scan rate: (a) 1 mV s<sup>-1</sup>, (b) 2 mV s<sup>-1</sup>, (c) 5 mV s<sup>-1</sup>, (d) 10 mV s<sup>-1</sup>, and (e) 20 mV s<sup>-1</sup>.

and enables determination of the diffusion coefficient of  $\text{NbF}_6^-$ . The obtained value of  $1.34 \times 10^{-7} \text{ cm}^2 \text{ s}^{-1}$  is close to that obtained from cyclic voltammetry. In the 44.4%  $\text{AlCl}_3$ –55.6% EMImCl ionic liquid at 313 K, the diffusion coefficient of  $\text{NbCl}_6^-$  was reported as  $4.98 \times 10^{-7} \text{ cm}^2 \text{ s}^{-1}$  [25]. This value is higher than that of  $\text{NbF}_6^-$  in the present study, which is probably due to the lower viscosity of the 44.4%  $\text{AlCl}_3$ –55.6% EMImCl ionic liquid (21 cP at 313 K) [26] than that of the BMPyrTFSA ionic liquid (72 cP at 298 K).

## 2.2. Electrochemical behavior of $\text{W(VI)F}_7^-$

Fig. 4 shows the cyclic voltammograms of a Pt electrode in BMPyrTFSA containing 61.8 mM of BMPyrWF<sub>7</sub>. The peak potential of the cathodic wave shifts to the negative potential with increase in scan rate from 1 to 20  $\text{mV s}^{-1}$ , suggesting that this is not a reversible reaction. If the reaction is totally irreversible,  $E_p^c - E_{p/2}^c$  is independent on scan rate [24], whereas the value of  $E_p^c - E_{p/2}^c$  increases with increase of scan rate. Thus, the present reaction is considered to be a quasi-reversible one. Table S2 lists the voltammetric parameters obtained for  $\text{WF}_7^-$ . According to the previous report on electrochemical behavior of  $\text{WCl}_6^-$  in the basic  $\text{AlCl}_3$ –EMImCl ionic liquid containing  $\text{KWCl}_6$  (or  $\text{WCl}_6$ ) [27],  $\text{WCl}_6^-$  is reduced to  $\text{WCl}_6^{2-}$  via a one-electron reaction at 0.45 V vs.  $\text{Al}^{3+}/\text{Al}$  in 66.7%  $\text{AlCl}_3$ –33.3% EMImCl melt. This suggests that the reduction from  $\text{W(V)}$  to  $\text{W(IV)}$  in the present system occurs at a more negative potential than  $-1.0$  V vs.  $\text{Ag}^+/\text{Ag}$  and the reduction current observed around  $-1.0$  V vs.  $\text{Ag}^+/\text{Ag}$  in Fig. 4 is probably assigned to the following reduction reaction.:



In order to estimate the diffusion coefficient of  $\text{WF}_7^-$ , chronoamperometry was performed at a Pt electrode. Fig. 5 shows the Cottrell plot, where the potential was stepped from  $-0.8$  to  $-1.5$  V vs.  $\text{Ag}^+/\text{Ag}$ . The linearity and zero-intercept of the plot indicates the validity of a simple diffusion controlled reaction. The value of  $D_R$  is calculated to be  $7.45 \times 10^{-8} \text{ cm}^2 \text{ s}^{-1}$  at 298 K with  $n = 1$ . The diffusion coefficients of some chlorotungstate anions,  $\text{WCl}_6^-$ ,  $\text{WCl}_6^{2-}$  and  $\text{W}_2\text{Cl}_9^{3-}$ , in basic 44.4 mol%  $\text{AlCl}_3$ –55.6% EMImCl ionic liquid at 313 K (21 cP) were reported to be  $(2.8 \pm 0.2) \times 10^{-7}$ ,  $(2.2 \pm 0.1) \times 10^{-7}$  and  $(1.5 \pm 0.1) \times 10^{-7} \text{ cm}^2 \text{ s}^{-1}$ , respectively [27].

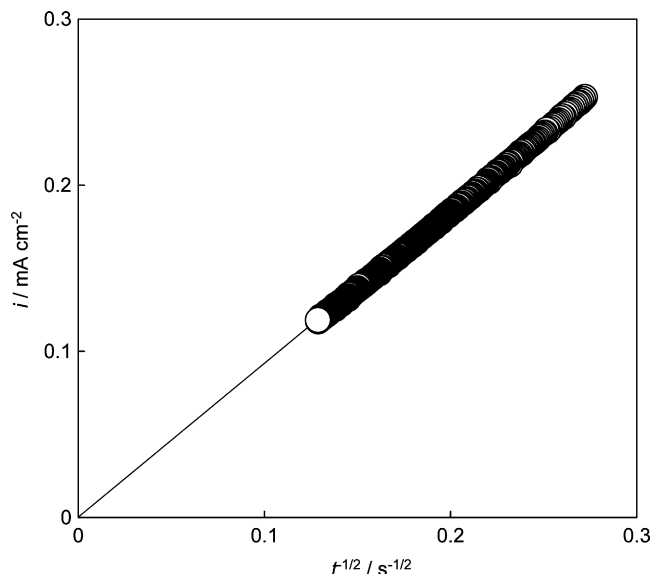


Fig. 5. The  $t^{1/2} - i$  plots for the reduction of  $\text{WF}_7^-$  in BMPyrTFSA containing 61.8 mM of BMPyrWF<sub>7</sub>.

These values for chlorotungstate anions are larger than that of  $\text{WF}_7^-$  in BMPyrTFSA at 298 K (76 cP), which is again explained by the difference in the viscosity of the two ionic liquids.

## 2.3. Electrochemical behavior of $\text{V(V)OF}_4^-$

The new salt, BMPyrVOF<sub>4</sub>, is a pale-yellow solid at room temperature. Differential scanning calorimetry (DSC) revealed that its melting point is 323 K. According to the previous study on the crystal structures of  $\text{CsVOF}_4$  [28] and  $\text{EMImVOF}_4$  [29],  $\text{VOF}_4^-$  is not a discrete anion in the solid state but forms the polymeric or oligomeric unit (the  $(\text{VOF}_4^-)_n$  chain in  $\text{CsVOF}_4$  and  $(\text{VOF}_4^-)_2$  dimer in  $\text{EMImVOF}_4$ ) via a weak  $\text{V} \cdots \text{F}$  interaction. Fig. 6 shows Raman spectra of (a) BMPyrVOF<sub>4</sub> (solid), (b) 1.53 M BMPyrVOF<sub>4</sub> in BMPyrTFSA (liquid), and (c) BMPyrTFSA (liquid). The vibrational frequency of  $1005 \text{ cm}^{-1}$  in the Raman spectrum of BMPyrVOF<sub>4</sub> is assigned to the  $\text{V}=\text{O}$  stretching mode and is similar to that observed for  $\text{EMImVOF}_4$  ( $1012 \text{ cm}^{-1}$  in Raman spectrum), suggesting  $\text{VOF}_4^-$  forms a oligomeric unit as observed in the previous study [29]. The Raman spectrum (b) in Fig. 6 shows two peaks in this region. The vibrational mode at  $1005 \text{ cm}^{-1}$  can be assigned to the  $\text{V}=\text{O}$  stretching in  $(\text{VOF}_4^-)_2$  due to the similarity in frequency. The vibrational mode at  $1027 \text{ cm}^{-1}$  corresponds to the stronger  $\text{V}=\text{O}$  bond than that in  $(\text{VOF}_4^-)_2$  caused by the break of the dimeric anion. Although the Raman spectrum of the electrolyte used in the present study (17.0 mM BMPyrVOF<sub>4</sub> in BMPyrTFSA), unfortunately, does not show a clear peak assigned to the  $\text{V}=\text{O}$  stretching mode because of its low concentration, the break of the polymeric  $\text{VOF}_4^-$  is highly possible in this diluted electrolyte.

Fig. 7 shows cyclic voltammograms of a Pt electrode in BMPyrTFSA containing 17.0 mM of BMPyrVOF<sub>4</sub>. Table S3 lists the voltammetric parameters obtained for  $\text{VOF}_4^-$ . The previous report mentioned that the one-electron reduction of  $\text{V(V)}$  species to  $\text{V(IV)}$  species was observed around 0.4 V vs.  $\text{Al}^{3+}/\text{Al}$  in 50%  $\text{AlCl}_3$ –50.0% EMImCl at 298 K [14]. Thus, the most probable reaction for the reduction wave around  $-1.0$  V in Fig. 7 is

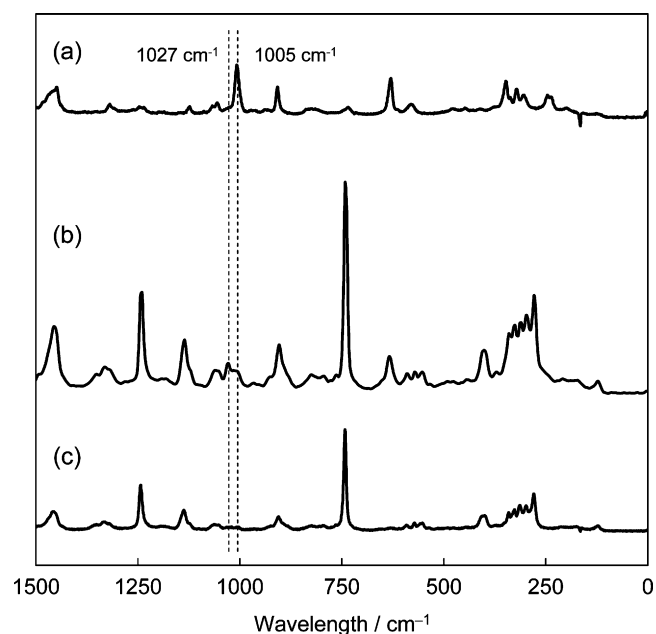
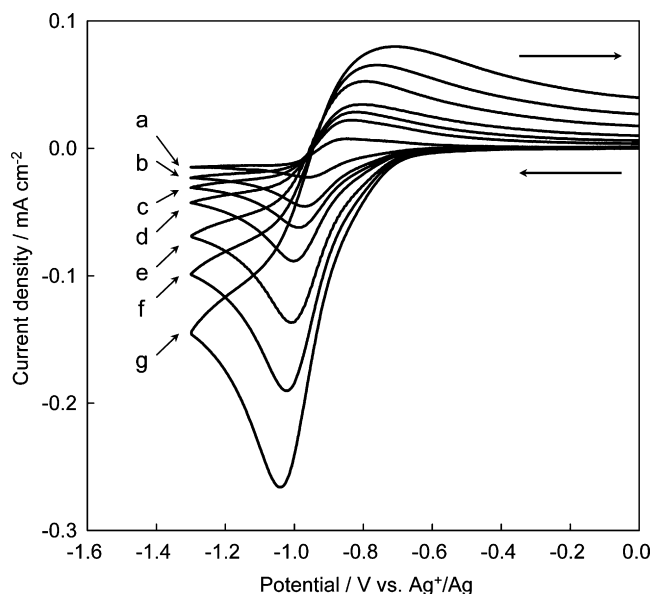


Fig. 6. Raman spectra of (a) BMPyrVOF<sub>4</sub> (solid), (b) BMPyrTFSA containing 1.53 M BMPyrVOF<sub>4</sub> (liquid), and (c) BMPyrTFSA (liquid).



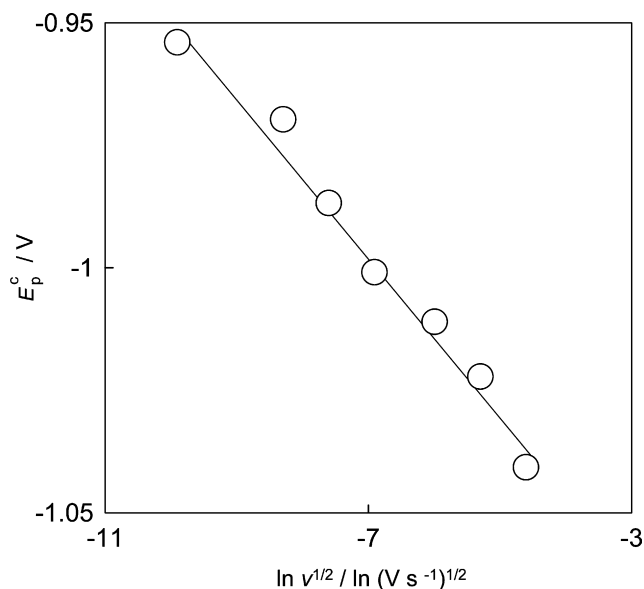
**Fig. 7.** Cyclic voltammograms of a Pt electrode in BMPyrTFSA containing 17.0 mM of BMPyrVOF<sub>4</sub> at 298 K. Scan rate: (a) 0.1 mV s<sup>-1</sup>, (b) 0.5 mV s<sup>-1</sup>, (c) 1 mV s<sup>-1</sup>, (d) 2 mV s<sup>-1</sup>, (e) 5 mV s<sup>-1</sup>, (f) 10 mV s<sup>-1</sup>, and (g) 20 mV s<sup>-1</sup>.

$E_p^c$  shifts to the negative potential with increase in scan rate. Fig. 8 shows the  $\ln v^{1/2} - E_p^c$  plot for the reduction of VOF<sub>4</sub><sup>-</sup>. The linear relationship between  $\ln v^{1/2}$  and  $E_p^c$  indicates that this reaction is totally irreversible as is given by Eq. (7) [24]:

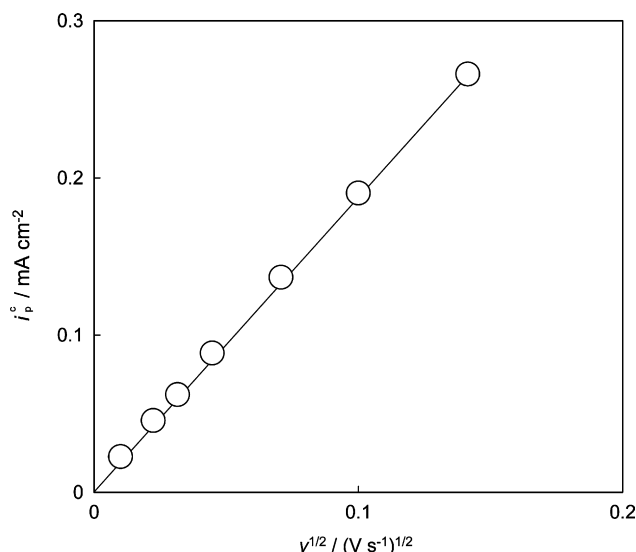
$$E_p^c = E^{0'} - \frac{RT}{\alpha n_\alpha F} \left[ 0.780 + \ln \left( \frac{D^{1/2}}{k^0} \right) + \ln \left( \frac{\alpha n_\alpha F v}{RT} \right)^{1/2} \right] \quad (7)$$

where  $E^{0'}$  is the standard formal potential of the redox couple,  $R$  is the gas constant,  $T$  is the temperature,  $\alpha$  is the transfer coefficient,  $n_\alpha$  is the number of electrons involved in the rate determining step,  $F$  is the Faraday constant, and  $k^0$  is the standard heterogeneous rate constant. The product,  $\alpha n_\alpha$  is estimated from Eq. (8) [24]:

$$\left| E_p^c - E_{p/2}^c \right| = \frac{47.7}{\alpha n_\alpha} \quad (8)$$



**Fig. 8.** The  $\ln v^{1/2} - E_p^c$  plots for the reduction of VOF<sub>4</sub><sup>-</sup> in BMPyrTFSA containing 17.0 mM of BMPyrVOF<sub>4</sub>.



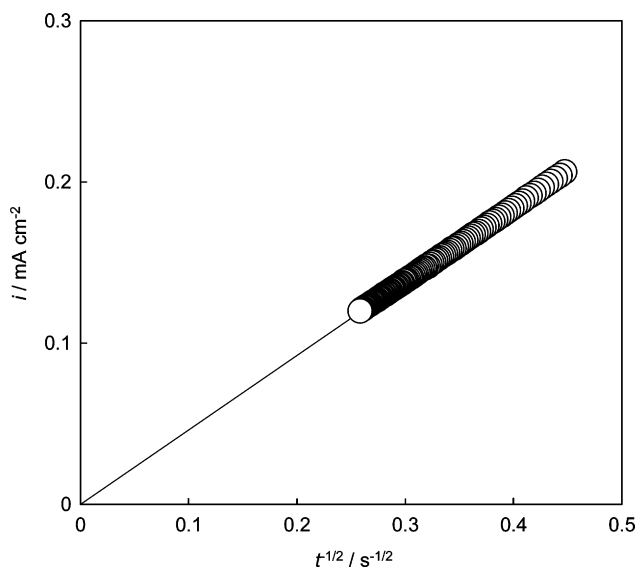
**Fig. 9.** The  $v^{1/2} - i_p^c$  plots for the reduction of VOF<sub>4</sub><sup>-</sup> in BMPyrTFSA containing 17.0 mM of BMPyrVOF<sub>4</sub>.

The value of  $\alpha n_\alpha$  is estimated to be 0.49 at the scan rate of 0.1 mV s<sup>-1</sup>, which suggests the number of electrons transferred in the rate determining step is one, where  $\alpha$  is assumed to be 0.5. The  $v^{1/2} - i_p^c$  plot shown in Fig. 9 confirms the linear relationship between them, and allows the determination of the diffusion coefficient from the slope by Eq. (9) [24]:

$$i_p^c = (2.99 \times 10^5) n (\alpha n_\alpha)^{1/2} D^{1/2} C v^{1/2} \quad (9)$$

The obtained diffusion coefficient of VOF<sub>4</sub><sup>-</sup> is  $2.81 \times 10^{-7}$  cm<sup>2</sup> s<sup>-1</sup> at 298 K.

Chronoamperometry was also performed using a Pt electrode to determine the diffusion coefficient of VOF<sub>4</sub><sup>-</sup>. Fig. 10 shows the  $t^{-1/2} - i$  plots in the case that the electrode potential was stepped to -1.2 V vs. Ag<sup>+</sup>/Ag. The linearity and zero-intercept obtained from the plot indicate that the Cottrell equation (Eq. (4)) holds in the present case. The diffusion coefficient is determined to be  $2.49 \times 10^{-7}$  cm<sup>2</sup> s<sup>-1</sup> at 298 K, which is the similar value obtained by voltammetry. According to the previous study [30], the



**Fig. 10.** The  $t^{-1/2} - i$  plots for the reduction of VOF<sub>4</sub><sup>-</sup> in BMPyrTFSA containing 17.0 mM of BMPyrVOF<sub>4</sub>.

**Table 1**

The diffusion coefficient ( $D$ , obtained by chronoamperometry) and Stokes radius ( $r_s$ ) of  $\text{NbF}_6^-$ ,  $\text{WF}_7^-$ , and  $\text{VOF}_4^-$  in BMPyrTFSA and of related species in a chloroaluminate ionic liquid. The viscosities ( $\eta$ ) of the ionic liquid systems are also listed.

Species	System	Temperature, K	$10^8 D$ , $\text{cm}^2 \text{s}^{-1}$	$\eta$ , cP	$r_s$ , nm	Reference
$\text{Nb(V)F}_6^-$	BMPyrTFSA	298	13.4	72	0.22	This work
$\text{Nb(V)Cl}_6^-$	49.0% $\text{AlCl}_3$ –51.0% EMImCl	313	82.1	13	0.21	[25,26]
$\text{Nb(V)Cl}_6^-$	44.4% $\text{AlCl}_3$ –55.6% EMImCl	313	49.8	21	0.22	[25,26]
$\text{W(VI)F}_7^-$	BMPyrTFSA	298	7.45	76	0.38	This work
$\text{W(V)Cl}_6^-$	44.4% $\text{AlCl}_3$ –55.6% EMImCl	313	28	–	0.38	[26,27]
$\text{W(IV)Cl}_6^{2-}$	44.4% $\text{AlCl}_3$ –55.6% EMImCl	313	22	–	0.49	[26,27]
$\text{V(V)OF}_4^-$	BMPyrTFSA	298	24.9	74	0.12	This work
$\text{V(II)}_{\text{solv}}$	66.7% $\text{AlCl}_3$ –33.3% EMImCl	353	24.1	4.8	2.22	[30]

diffusion coefficients of  $\text{V(II)}_{\text{solv}}$  in acidic 66.7 mol%  $\text{AlCl}_3$ –33.3% EMImCl ionic liquid at 353 K is  $2.41 \times 10^{-7} \text{ cm}^2 \text{ s}^{-1}$ . This value is similar to that of  $\text{VOF}_4^-$  in BMPyrTFSA, although the viscosity of 66.7 mol%  $\text{AlCl}_3$ –33.3% EMImCl at 353 K (4.8 cP) is much lower than that of BMPyrTFSA (74 cP). Difference in the coordination environment around metal species may lead to this coincidence.

#### 2.4 Stokes radius of the diffusion species

The Stokes–Einstein equation given in Eq. (10) is applied to  $\text{NbF}_6^-$ ,  $\text{WF}_7^-$ , and  $\text{VOF}_4^-$  in the BMPyrTFSA ionic liquid system:

$$r_s = \frac{kT}{6\pi\eta D} \quad (10)$$

where  $r_s$  is the Stokes radius,  $\eta$  is the viscosity, and  $k$  is the Boltzmann constant. For this purpose, viscosities of BMPyrTFSA containing 29.2 mM BMPyr $\text{NbF}_6$ , 61.8 mM of BMPyr $\text{WF}_7$ , or 17.0 mM of BMPyr $\text{VOF}_4$  were measured (72, 76, or 74 cP, respectively). Table 1 lists the calculated Stokes radii of  $\text{NbF}_6^-$ ,  $\text{WF}_7^-$ , and  $\text{VOF}_4^-$  [25–27]. The Stokes radii for several related chloro-complex anions in  $N\%\text{AlCl}_3$ –(100– $N$ )%EMImCl ( $N = 44.4$ , 49.0, and 66.7%) are also listed for comparison [30]. The Stokes radii of  $\text{NbF}_6^-$  (0.22 nm) in BMPyrTFSA and  $\text{NbCl}_6^-$  (0.21 nm) in 49.0% $\text{AlCl}_3$ –51.0%EMImCl are close to each other. Although the size of  $\text{NbF}_6^-$  determined in a crystal structure (Nb–F bond length:  $\sim 0.188$  nm [31–33]) is smaller than that of  $\text{NbCl}_6^-$  (Nb–Cl bond length:  $\sim 0.235$  nm [34]), the difference in cation–anion interactions, namely, the form of the ion pair or ion aggregate, and the difference in temperature probably influence the  $r_s$  values. The Stokes radius of  $\text{WF}_7^-$  (0.38 nm) is similar to that of  $\text{WCl}_6^-$  (0.38 nm), and smaller than that of  $\text{WCl}_6^{2-}$  (0.49 nm). It should be noted that the  $r_s$  value for  $\text{WF}_7^-$  (0.38 nm) is significantly larger than that for  $\text{NbF}_6^-$  (0.22 nm), even taking into account the larger ion size of  $\text{WF}_7^-$  than that of  $\text{NbF}_6^-$  [35]. This suggests that these species diffuse in a totally different form in BMPyrTFSA. The similar case was also seen for  $\text{NbCl}_6^-$  and  $\text{WCl}_6^-$  [27,29]. The  $r_s$  of  $\text{VOF}_4^-$  anion was calculated to be relatively small value of 0.12 nm. The small  $r_s$  size is explained by the weak interactions between  $\text{VOF}_4^-$  anion and solvent, which results in the large diffusion coefficient of  $\text{VOF}_4^-$ . The order of the Stokes radii of the anionic species obtained in this study follows the order of their ionic radii of the central atom ( $\text{V(V)}$  (0.060 nm) <  $\text{Nb(V)}$  (0.078 nm) <  $\text{W(VI)}$  (0.087 nm)) [36] although the coordination number and ligands (O or F) are different within the three species.

### 3. Conclusions

Electrochemical behavior of  $\text{NbF}_6^-$ ,  $\text{WF}_7^-$ , and  $\text{VOF}_4^-$  was studied in *N*-butyl-*N*-methylpyrrolidinium bis(trifluoromethylsulfonfyl)amide (BMPyrTFSA) ionic liquid at 298 K by cyclic voltammetry and chronoamperometry. Reduction of  $\text{NbF}_6^-$  at a Pt electrode proceeds via a one-electron reversible process,

suggesting that the product is  $\text{NbF}_6^{2-}$ . The diffusion coefficient of  $\text{NbF}_6^-$  is determined to be  $1.34 \times 10^{-7} \text{ cm}^2 \text{ s}^{-1}$ . The reduction of  $\text{WF}_7^-$  at a Pt electrode is a quasi-reversible process to  $\text{WF}_7^{2-}$ . The diffusion coefficient of  $\text{WF}_7^-$  is calculated to be  $7.45 \times 10^{-8} \text{ cm}^2 \text{ s}^{-1}$ . The reduction of  $\text{VOF}_4^-$  at a Pt electrode is an irreversible process to  $\text{VOF}_4^{2-}$  with the  $\alpha_{\text{red}}$  value of 0.49. The diffusion coefficient of  $\text{VOF}_4^-$  is calculated to be  $2.49 \times 10^{-7} \text{ cm}^2 \text{ s}^{-1}$ . From the Stokes–Einstein equation, the Stokes radii of  $\text{NbF}_6^-$ ,  $\text{WF}_7^-$ , and  $\text{VOF}_4^-$  are estimated to be 0.22, 0.38, and 0.12 nm, respectively. The significant difference in size suggests the different coordination environments around them.

## 4. Experimental

#### 4.1. General

Nonvolatile materials were handled under a dry and deoxygenated Ar atmosphere in a glove box. The fluorocomplex salts, BMPyr $\text{NbF}_6$  and BMPyr $\text{WF}_7$ , were synthesized by the reactions of *N*-butyl-*N*-methylpyrrolidinium fluorohydrogenate IL, BMPyr(FH) $_{2,3}\text{F}$ , and Lewis acid fluorides ( $\text{NbF}_5$  (Aldrich, purity 99%) and  $\text{WF}_6$  (Central Glass, purity 99.999%)) according to the literature [16]. The room temperature ionic liquid, BMPyrTFSA (Kanto Kagaku), was dried under vacuum at 373 K for two days. The fluorometallate and oxofluorometallate sources were weighed and added to BMPyrTFSA, followed by agitation overnight. Electrochemical measurements were carried out in a PFA (tetrafluoroethylene–perfluoroalkylvinylether copolymer) cell ( $\sim 2$  mL) under the Ar atmosphere at 298 K with the aid of an electrochemical measurement system HZ-3000 (Hokuto Denko). The materials for working and counter electrodes were a Pt plate (0.18  $\text{cm}^2$ ) and a glassy carbon rod (0.36  $\text{cm}^2$ ), respectively. The reference electrode was made of a silver wire immersed in EMImBF $_4$  containing 0.05 M  $\text{AgBF}_4$  separated from the electrolyte by a PTFE filter. The typical resistance of the electrolyte was ca. 100  $\Omega$  and the resulting ohmic drop was negligible because of the small area of the working electrode. Viscosity was measured by a cone-plate rheometer DV-II + Pro (Brookfield Engineering Laboratories Inc.).

#### 4.2. Synthesis of BMPyr $\text{VOF}_4$

The  $\text{VOF}_4^-$  source, BMPyr $\text{VOF}_4$ , was prepared in the following manner [25]. Vanadium oxide trifluoride (Aldrich, purity 99%, 0.53 g (4.28 mmol)) loaded in one arm of a T-shaped PFA was slowly added onto BMPyr(FH) $_{2,3}\text{F}$  (4.28 mmol) in the other arm at room temperature. After the addition of  $\text{VOF}_3$ , the obtained liquid was stirred for 5 h. A pale-yellow powder sample was obtained after removal of liberated HF under dynamic vacuum at 340 K. Vibrational spectroscopy and elemental analysis identified the solid as BMPyr $\text{VOF}_4$ . Anal. Calcd. for  $\text{C}_9\text{H}_{20}\text{N}_1\text{V}_1\text{O}_1\text{F}_4$ : C, 37.90; H, 7.07; N, 4.91. Found: C, 37.86; H, 7.05; N, 4.93. Raman (solid) for  $\text{VOF}_4^-$  (frequency/ $\text{cm}^{-1}$  (Relative intensity): 1005 (m), 628 (m),

345 (s), 318 (w), 242 (m), and 234 (m); IR for  $\text{VOF}_4^-$  (frequency/ $\text{cm}^{-1}$  (relative intensity): 999 (m), 632 (s), and 590 (s), where s, m and w for relative intensity denote strong, medium and weak, respectively.

#### Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at [doi:10.1016/j.jfluchem.2011.02.012](https://doi.org/10.1016/j.jfluchem.2011.02.012).

#### References

- [1] J.S. Wilkes, J.A. Levisky, R.A. Wilson, C.L. Hussey, *Inorg. Chem.* 21 (1982) 1263–1264.
- [2] I.W. Sun, J.R. Sanders, C.L. Hussey, *J. Electrochem. Soc.* 136 (1989) 1415–1419.
- [3] R.T. Carlin, R.A. Osteryoung, J.S. Wilkes, J. Rovang, *Inorg. Chem.* 29 (1990) 3003–3009.
- [4] T. Tsuda, C.L. Hussey, G.R. Stafford, J.E. Bonevich, *J. Electrochem. Soc.* 150 (2003) C234–C243.
- [5] I. Mukhopadhyay, C.L. Aravinda, D. Borissov, W. Freyland, *Electrochim. Acta* 50 (2005) 1275–1281.
- [6] Y. Katayama, K. Ogawa, T. Miura, *Electrochemistry* 73 (2005) 576–578.
- [7] H. Ohno (Ed.), *Electrochemical Aspects of Ionic Liquids*, John Wiley & Sons, New Jersey, 2005.
- [8] S. Zein El Abedin, F. Endres, *ChemPhysChem* 7 (2006) 58–61.
- [9] S. Zein El Abedin, E.M. Moustafa, R. Hempelmann, H. Natter, F. Endres, *Chem. Phys. Chem.* 7 (2006) 1535–1543.
- [10] M. Yamagata, N. Tachikawa, Y. Katayama, T. Miura, *Electrochim. Acta* 52 (2007) 3317–3322.
- [11] C. Nanjundiah, K. Shimizu, R.A. Osteryoung, *J. Electrochem. Soc.* 129 (1982) 2474–2480.
- [12] R. Fukui, Y. Katayama, T. Miura, *Electrochemistry* 73 (2005) 567–569.
- [13] W. Simka, D. Puszczczyk, G. Nawrat, *Electrochim. Acta* 54 (2009) 5307–5319.
- [14] D.M. Ryan, T.L. Riechel, T. Welton, *J. Electrochem. Soc.* 149 (2002) A371–A378.
- [15] M. Yamagata, Y. Katayama, T. Miura, *J. Electrochem. Soc.* 153 (2006) E5–E9.
- [16] T. Kanatani, R. Ueno, T. Nohira, R. Hagiwara, *J. Fluorine Chem.* 130 (2009) 979–984.
- [17] Q. Zhiyu, T. Pierre, *J. Appl. Electrochem.* 15 (1985) 259–265.
- [18] S. Senderoff, G.W. Mellors, *J. Electrochem. Soc.* 113 (1966) 66–71.
- [19] V.I. Konstantinov, E.G. Polyakov, P.T. Stangrit, *Electrochim. Acta* 26 (1979) 445–448.
- [20] F. Matthesen, E. Chrstensen, J.H. von Barner, N.J. Bjerrum, *J. Electrochem. Soc.* 143 (1996) 1793–1799.
- [21] V. Van, A. Silný, J. Híveš, V. Daněk, *Electrochem. Commun.* 1 (1999) 295–300.
- [22] C. Rosenkilde, A. Vik, T. Østvold, E. Chritensen, N. Bjerrum, *J. Electrochem. Soc.* 147 (2000) 3790–3800.
- [23] U. Stöhr, W. Freyland, *Electrochim. Acta* 44 (1999) 2199–2207.
- [24] A.J. Bard, L.R. Faulkner, *Electrochemical Methods*, 2nd ed., John Wiley & Sons, New York, 2001.
- [25] I.W. Sun, C.L. Hussey, *Inorg. Chem.* 28 (1989) 2731–2737.
- [26] A.A. Fannin, D.A. Floreani, L.A. King, J.S. Landers, B.J. Piersma, D.J. Stech, R.L. Vaughn, J.S. Wilkes, J.L. Williams, *J. Phys. Chem.* 88 (1984) 2614–2621.
- [27] T.B. Scheffler, C.L. Hussey, *Inorg. Chem.* 23 (1984) 1926–1932.
- [28] G.W. Bushnell, K.C. Moss, *Can. J. Chem.* 50 (1972) 3700–3705.
- [29] T. Kanatani, K. Matsumoto, R. Hagiwara, *Eur. J. Inorg. Chem.* (2010) 1049–1055.
- [30] T. Tsuda, C.L. Hussey, *J. Min. Met.* 39 (2003) 3–22.
- [31] R.W. Berg, *Coord. Chem. Rev.* 113 (1992) 1–130.
- [32] M.B. de Bournonville, B. Bizot, J. Chassaing, M. Quarton, *J. Solid State Chem.* 62 (1986) 212–219.
- [33] K. Matsumoto, R. Hagiwara, Z. Mazej, P. Benkič, B. Žemva, *Solid State Sci.* 8 (2006) 1250–1257.
- [34] A. Hagebach, J. Strähle, *Z. Anorg. Allg. Chem.* 627 (2001) 726–730.
- [35] S. Giese, K. Seppelt, *Angew. Chem. Int. Ed. Engl.* 33 (1994) 461–463.
- [36] R.D. Shannon, *Acta Crystall.* A32 (1976) 751–767.