INTRODUCTION

Extensive studies have been done by many workers, in the search of lithium ion conducting superionic solids because of their application potentialities in high power miniaturized electrochemical cells. We have also been investigating these solids for the last two decades. This paper presents the study of electrical transport with the molar magnetic susceptibility ($X_M$) and dielectric constant (K) measurements.

MATERIAL

Preparation and experimental technique

To prepare the studied system the base materials Li$_2$O: P$_2$O$_5$ and WO$_3$ were first procured from Rare and Research Chemical, Bombay and Chempure, Calcutta with stated purity of 99.99 percent. The base materials were taken in stoichiometric amount and mixed thoroughly. The mixed material was then fired around 1050K for 48h with one intermediate grinding. The material was then melted, shaken thoroughly and allowed to cool slowly to get solidified melt. X-ray diffraction shows that no unreacted starting material was left and single phase compound is formed. The measurement on electrical conductivity ($\sigma$), Seebeck coefficient (S) and dielectric constant (K) were performed on solidified melt whereas molar magnetic susceptibility ($X_M$) was performed on powdered sample from 400K to the melting point of the solid. The details of sample holder and measurements have been described elsewhere.

RESULTS AND DISCUSSION

The electrical conductivity ($\sigma_{dc}$) as a function of frequency (50Hz, 100Hz, 1kHz, 3kHz and 10kHz) has been measured at constant temperature. The results are not shown. For comparison $\sigma_{dc}$ values at corresponding temperature are also given in same figure. It is seen from this figure that there is no difference between $\sigma_{dc}$ values at different frequencies. Also $\sigma_{dc}$ is almost same as $\sigma_{ac}$. This result indicates that grain-
boundary effects are not very significant in this solid. To investigate the nature of charge carrier $\sigma_{dc}$ has been measured as a function of time at a constant temperature. This study has been preformed at six widely separated temperatures. The results are shown in Fig. 1. It is seen form this figure that $\sigma_{dc}$ decreases with time and tends to attain a constant value after a long time. This time of constancy becomes small at lower temperature. This indicates that the compound is essentially mixed conductor. The value extrapolated to $t=0$ gives total (electronic + ionic) conductivity ($\sigma$) where as the value obtained for $t\to\infty$ gives electronic part of total conductivity. Using he plot of $\sigma_{dc}$ vs $T^{-1}$ s values $\sigma_e$ have been obtained. The ratio ($r$) is then calculated using equation 1 at five to six widely separated temperature.

$$r = \frac{\sigma_i}{\sigma_e} = \frac{\sigma}{\sigma_e} - 1 \quad \text{...(1)}$$

The plot of log $r$ with temperature is shown in Fig.2. It is seen from this figure that $r$ increases with temperature becomes very fast for $T>890K$ and at higher temperature $T>1000K$ it tends to decrease with temperature.

$\sigma$ and $S$ measurements on three to four solidified melts from different lots have been done as a function of temperature. No hysteresis was observed and obtained $\sigma$ and $S$ values are almost in both heating and cooling cycles. The results are shown as log $\sigma T$ vs $T^{-1}$ plots in Fig. 3. It is seen from this figure that $s$ values is high being $1.85 \times 10^2$ at 50K. The material is hygroscopic. The log $\sigma T$ vs $T^{-1}$ plot is linear between temperature range 415 K to 765K after that there is step and continuous increase of log $\sigma$ and then conductivity increase slowly till the melting point. 1110K of the solid. The linear region of the plot can be represented by the equation 2.

$$\sigma T = C \exp (-E_a/kT) \quad \text{...(2)}$$

The values of $E_a$ and $C$ are 0.37 ev and $1.87 \times 10^3 \Omega^{-1} \text{m}^{-1}$ K and 0.45 ev and $4.40 \times 10^5 \Omega^{-1} \text{m}^{-1}$ K for temperature range 415 K to 765K and 765 K to 1110K respectively. The $S$ vs $T^{-1}$ plot is also linear in the temperature interval 500K to 760K and 770K to 1110K. The linear region can be represented by the equation 3.

$$S = \frac{\eta}{eT} + H \quad \text{...(3)}$$

The value of $\eta$ and $H$ in the first region are 0.60 eV and -0.00 mVK$^{-1}$ and in the second region-0.40 eV and -0.02 mVK$^{-1}$. The sign of $S$ in the superionic region indicating that the positive ions are the main entity of charge carrier.

The ratio of ionic electronic conductivities at different temperatures have been evaluated from time dependence study of $\sigma_{dc}$. Using these values we have separated ionic ($\sigma_i$) and electronic ($\sigma_e$) parts of electrical conductivity. Plot of log $\sigma_i T$ vs $T^{-1}$ is shown in Fig. 3. by dotted line. It is seen from this figure that there is almost no difference between $\sigma_i$ and $\sigma$ at higher temperature ($T>800K$). However, they differ to some extent in lower temperature range. In the second region $\sigma$ is very high ($100 \Omega^{-1} \text{m}^{-1}$). The ratio $r$ is of the order of 10$^3$ and essentially $\sigma_i=\sigma$. Thus this compound is pure ionic conductor. Thermo electric power in this range is negative indicating cations to be the mobile charge carrier. Thus from the value of $\sigma$ and ionic nature of conductivity we can say that the compound is a good solid electrolyte. The span of superionic phase is 160K (950-1110K). The transition to superionic phase takes place at 950K. The linear regions of log $\sigma T$ and $S$ vs $T^{-1}$ plots can be represented by the relation.

$$QS = \frac{\eta}{eT} + H \quad \text{...(4)}$$

$$\frac{\eta s T}{e} = C \exp (-h /kt) \quad \text{...(5)}$$

The values of $Q$ and $h_m$ are 0.42 eV and 0.47 eV with a value of $\sigma_i$ at 1040K as 35 $\Omega^{-1} \text{m}^{-1}$. Thus $h_m$ is slightly lager than $Q$. The difference is of the order of polaronic binding energy$^{18}$. Such as result is predicted by Extented latic gas model. In the lower temperature range of electronic contribution is small (from 20 to 10 present). Thus there is dominance of ionic conductivity. The sign of $S$ in this temperature range is positive. Hence current carries are negatively charged. This can happen when either cation vacancies of anions are mobile in this temperature
Fig. 1: Plot of Logarithm of conductivity (log $\sigma$) Vs Time (t) of the system Li$_2$O: P$_2$O$_5$:WO$_3$

Fig. 2: Plot of Logarithm of Ionic of Electronic conductivity (log $\tau$) Vs Absolute Temperature (T) of the system Li$_2$O: P$_2$O$_5$:WO$_3$

Fig. 3: Plot of logarithm of product of conductivity and Temperature (log $\sigma T$) and Thermoelectric power ($s$) Vs Inverse of absolute temperature (T$^{-1}$) of the system Li$_2$O: P$_2$O$_5$:WO$_3$

Fig. 4: Plot of Molar magnetic susceptibility ($\chi_m$) and logarithm of dielectric (log $K$) Vs absolute temperature (T) for the system Li$_2$O: P$_2$O$_5$:WO$_3$. 

range. Motion of anions at lower temperature is less probable. Hence the conduction seems to be dominated by cation vacancies or Schottky type defects.

The log $\sigma$ vs $T^{-1}$ plot (Fig. 3.) is similar to the plot of log $\sigma$ vs $T^{-1}$. $\sigma$ jumps by several order of magnitude around particular temperature. The linear region can be represented by the equation 6.

$$T\sigma_e = \sigma_0 \exp (-W/kT) \quad \text{(6)}$$

The value of $\sigma_0$ and $W$ are $3.08 \times 10^3 \ \Omega^{-1} \ m^{-1}$ and 0.51 eV.

The $\chi'_m$ and K studies are performed on two to these samples prepared in different lots. The $\chi'_m$ and log K plots are shown in Fig. 4. It is seen from that $\chi'_m$ increases very slowly up to 770K, shows a peak at 950K then decreases with increase of temperature. The value of $\chi'_m$ is throughout negative. Similar trend of variation is observed in log K vs T. The value of K is 55 at 500K. It increase with temperature up to 950K then decreases slowly indicating an abnormality at 945K as observed in log $\sigma$T vs $T^{-1}$ plot. The studied superionic system is ionic compound and contain no magnetic ions. Thus it is area diamagnetic as has been confirmed by the negative value of $\chi'_m$. Their diamagnetism depends upon its bonding configuration. The onset of disordering at phase transition disrupts the bonding configuration and leads to an abrupt change in $\chi'_m$. Thus the temperature around which anomaly appears is also confirmed by K and $\sigma$ plots.

REFERENCES