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Influence of lactose on the diffusion of calcium ions at physiological temperature

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ABSTRACT

Mutual diffusion coefficients for calcium chloride (0.100 mol dm\(^{-3}\)) in aqueous solutions containing lactose at various concentrations (from 0.005 to 0.200 mol dm\(^{-3}\)) have been measured at 37 °C (physiological temperature), by using a conductimetric cell coupled to an automatic system to follow the diffusion. This cell uses an open-ended capillary method based on the measurement of the electrical resistance of a solution placed inside the capillaries at recorded times. The analysis of the CaCl\(_2\) diffusion coefficient values obtained suggests the presence of some CaCl\(_2\)/lactose aggregates in the media, which are influenced by the temperature.

Keywords: Lactose; Calcium chloride; Solutions; Mutual diffusion coefficient; Transport properties.
1. Introduction

Lactose, a disaccharide derived from the condensation of galactose and glucose, is not only a technologically important compound, but also has biological, medical, pharmaceutical, food and biomedical applications (Swartz, M.L., Bernhard, R.A., & Nickerson, T.A., 1978; Sano, Y., & Yamamoto, S., 1993; Banipal, P.K., Banipal, T.S., Lark, B.S., & Ahluwalia, J.C., 1997; Moran, G.R., Jeffrey, K.R., Thomas, J.M., & Stevens, J.R., 2000) due to its capacity to interact with different metal ions involved in many biochemical reactions. It is the most important carbohydrate in milk of a large number of mammals. Lactose intolerance is a dysfunction that leads to a reduced calcium absorption, which can be associated with weight-bearing bones fractures, particularly in female human subjects (Honkaner, R., Kröger, H., Alhava, E., Turpeinen, P., Tuppurainen, M., & Saarikoski, S., 1997). As a result, people suffering from this condition have to supplement their calcium ingestion to reach the adequate physiological calcium levels.

Calcium plays a major role in bone structure and bone recalcification, which are continuous processes declining with age. Osteopenia, or low mineral density of the bones, must be addressed early since the calcium osteo-cycle is regulated by numerous factors, vitamin D being the most important one (Lieben, L., & Carmeliet, G., 2013), and skeletal metabolic diseases can cause a wide range of complications including pain, fracture, and can even be lethal (Imel, E.A., DiMeglio, L.A., & Burr, D.B., 2014).

A positive association between lactose intake and the enhancing of the calcium osteo-fixation, as well as the increasing of the trans-epithelial calcium transport was reported by Armbrecht (Armbrecht, H.J., 1987). Work by Schafsma et al. suggests that even
people with vitamin D-deficiency, the beneficial lactose effect can be noted (Schaafsma, G., Visser, W.J., Dekker, P.R., & VanSchaik, M., 1987). Also, lactose was reported as a superior carbohydrate in this role, when tested in calcium-deficient rats (Hämäläiner, M.M., Knuuttila, M., Svanberg, M., & Koskien, T., 1990).

Numerous studies regarding the thermodynamic properties of lactose binary aqueous solutions have been performed. Nevertheless, transport data related to aqueous solutions containing this sugar are scarce in the literature. The characterization of transport properties, such as diffusion coefficients, is important to derive some type of structural information on these aqueous systems. In fact, they provide a direct measure of molecular mobility, an important factor to be considered when formulating sugar matrixes.


In a previous paper (Ribeiro, A.C.F., et al., 2011b) ternary mutual diffusion coefficients ($D_{11}$, $D_{22}$, $D_{12}$ and $D_{21}$) for aqueous solutions containing calcium ions in the presence of lactose, at $T = 298.15$ K, were determined and analyzed. Then, we could conclude that
the diffusion of the calcium ions in the presence of lactose may be affected by the
eventual formation of different aggregate species resulting from various equilibria
taking place in these media. We have considered it interesting to evaluate the effect of
temperature on the formation of such aggregates, for which a temperature of 310.15 K
was selected to carry the analysis forward under physiological conditions.

2. Materials and methods

2.1. Materials

Lactose monohydrate (BDH Chemicals, UK > 97 %) and calcium chloride (Sigma-
Aldrich, Germany, pro analyti > 99.9 %) were used as received, without further
purification. The solutions, prepared in calibrated volumetric flasks using ultrapure
water obtained with a Millipore (Germany) water purification system (model Milli-Q
Advantage A10) \( \kappa = (0.7-0.9) \times 10^{-4} \text{ S m}^{-1} \), were freshly prepared and de-aerated for
about 30 minutes before use.

2.2. Mutual diffusion coefficients, \( D \), measured by using the open-ended conductimetric
capillary cell

The open-ended conductimetric capillary cell technique has been previously used to
obtain mutual diffusion coefficient values for a wide variety of electrolytes (e.g. (Agar,
J.N., & Lobo, V.M.M., 1975; Ribeiro, A.C.F., Lobo, V.M.M., Azevedo, E.F.G., Miguel,
M.G., & Burrows, H.D., 2001; Ribeiro, A.C.F., Lobo, V.M.M., & Natividade, J.J.S.,
2002; Ribeiro, A.C.F., Lobo, V.M.M., Azevedo, E.F.G., Miguel, M.G., & Burrows,
H.D., 2003; Ribeiro, A.C.F. et al., 2005; Ribeiro, A.C.F., et al., 2006b)). Therefore, this
method has been described in great detail in previous papers, along with various operating conditions (Agar, J.N., et al., 1975; Veríssimo, L.M.P., et al., 2013), and only the most relevant points will be indicated here. Basically, the technique consists of two vertical capillaries each closed at one end by a platinum electrode (TE and BE, top and bottom electrodes, respectively), positioned one above the other with the open ends face to face at a distance of about 14 mm (Figure 1). The upper and lower tubes, surrounded by a bulk solution of concentration \( c \), are initially filled with solutions at concentrations 0.75 \( c \) and 1.25 \( c \), respectively. This bulk solution (c concentration) is contained in a glass tank (200 \( \times \) 140 \( \times \) 60 mm) immersed in a thermostatic bath at 37 °C. Perspex sheets, G, divide the tank internally and a glass stirrer, A, creates a slow lateral flow of the ambient solution across the open ends of both capillaries. The experimental conditions are such that the concentration at each of the open ends is equal to the ambient solution value \( c \), that is, the physical length of the capillary tube coincides with the diffusion path. This means that the required boundary conditions described in the literature to solve Fick’s second law of diffusion are applicable (Agar, J.N., et al., 1975). Therefore, the so-called \( \Delta l \) effect (Agar, J.N., et al., 1975) is reduced to negligible proportions. In our apparatus, diffusion is followed by measuring the value of the ratio \( w = R_t/R_b \), \( R_t \) and \( R_b \) being the electrical resistances of the upper and the lower tubes, respectively. This \( w \) value is measured by using a digital voltmeter (Solartron, UK, DVM 7061 with 6 1/2 digits). A power source (Elgar, USA, 121B/400SD) supplies a 30 V sinusoidal signal at 4 kHz, stable within 0.1 mV, to a potential divider that applies a 250 mV signal to the platinum electrodes in the top and bottom capillaries. By measuring the voltages \( V' \) and \( V'' \) from both the top and the bottom electrodes with respect to a central electrode, ME, the DVM can calculate \( w \).
In order to measure the differential mutual diffusion coefficient $D$ at a given concentration $c$, the bulk solution of concentration $c$ is prepared by mixing 1 l of ‘top’ solution with 1 l of ‘bottom’ solution, accurately measured.

Initially, the glass tank and the two capillaries are filled with $c$ solution, immersed in the thermostatic bath, and allowed to come to thermal equilibrium. The resistance ratio $w$ measured under these conditions ($w = w_\infty$) with solutions in both capillaries at concentration $c$, accurately gives the quantity $\tau_\infty = 10^4 / (1 + w_\infty)$.

Afterwards, the capillaries are filled with the ‘top’ and the ‘bottom’ solutions, which are then allowed to diffuse into the ‘bulk’ solution. Resistance ratio readings are automatically recorded at various times, beginning 1000 min after the start of the experiment, to determine the quantity $\tau = 10^4(1+w)$ as $\tau$ approaches $\tau_\infty$. The diffusion coefficient is then evaluated by using a linear least-squares procedure to fit the data and, finally, an iterative process is applied using 20 terms of the expansion series of Fick’s second law for the present boundary conditions. The theory developed for this capillary cell has been previously reported (Agar, J.N., et al., 1975).

3. Results and discussion

Diffusion coefficients, $D$, and their respective standard deviations, $S_D$, for CaCl$_2$ 0.100 mol dm$^{-3}$ in aqueous solutions containing lactose at various concentrations (0.005 mol dm$^{-3}$, 0.010 mol dm$^{-3}$, 0.025 mol dm$^{-3}$, 0.050 mol dm$^{-3}$, 0.100 mol dm$^{-3}$ and 0.200 mol dm$^{-3}$) at 37 ºC are shown in Table 1. For comparison, data at 25 ºC (Barros, M.C.F., et al., 2013) obtained with similar conditions are also included. For brevity, we will indicate as 1 and 2 the lactose and CaCl$_2$ species, respectively (the solvent,
component 0, is not included). Each $D$ value is the mean of at least four independent measurements. Since the error limits of our results should be close to the imprecision, the experimental uncertainty was 1-3%.

The following polynomial in $c_1^{1/2}$ was used to fit our data by a least squares procedure,

$$D/10^{-9} \text{ m}^2 \text{ s}^{-1} = 1.454 - 0.252 \ c_1^{1/2} + 0.007 \ c_1$$

$$R^2 = 0.998$$

where $c_1$ and $D$ represent the concentration of lactose and the diffusion coefficient of cadmium chloride in the different aqueous solutions containing this carbohydrate, respectively. The goodness of the fit (obtained with a confidence interval better than 98 %) was assessed by both the excellent correlation coefficient, $R^2$, and the low standard deviation (< 1 %) found. Moreover, the limiting $D^0$ value calculated by extrapolating these experimental data to $c_1 \to 0 \ (D^0 = 1.454 \times 10^{-9} \text{ m}^2 \text{ s}^{-1})$ agrees well with the measured $D$ value ($D = 1.440 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$) for solutions containing only CaCl$_2$ at $c_2 = 0.100 \text{ mol dm}^{-3}$ (deviation of 0.97 %) (Ribeiro, A.C.F., et al., 2008).

From the difference between the diffusion measurements for CaCl$_2$ at both temperatures in aqueous solutions in the presence and absence of lactose (measured as the percentage difference, $\Delta D/D$ %) (Table 1), it can be verified that the diffusion behaviour of calcium chloride in aqueous solutions is affected by the presence of the lactose molecules. In fact, for both temperatures and under the present experimental conditions, when lactose concentrations $c$ are $\geq 0.05 \text{ mol dm}^{-3}$, the diffusion coefficient of CaCl$_2$ continuously decreases with increasing lactose concentration, especially at 25 ºC, for which this percentage reaches the maximum difference (i.e., $\Delta D/D = -14.7 \%$) at 0.200 mol/dm$^3$ of
lactose. At 37 ºC the behaviour observed is the same, although the values for the $\Delta D/D$ ratio are less than at 25 ºC (i.e., $\Delta D/D = -6.7\%$ at $c_2 = 0.200\ \text{mol/dm}^3$). It is also noted that at concentrations $c < 0.05\ \text{mol dm}^{-3}$, the diffusion coefficient of CaCl$_2$ did not significantly change at either temperature.

The decrease of the diffusion coefficients of calcium chloride with increasing concentration of lactose in these media may be interpreted on the basis of the formation of new species (e.g. ion pairs) resulting, mainly, from the interactions of Ca$^{2+}$ cations with lactose. This may lead to a reduced mobility of these species through the liquid and, consequently, a lower diffusion coefficient value.

In relation to the small decrease found in the experimental $D$ values of CaCl$_2$ in the presence of lactose at 37 ºC, at all concentrations studied (Table 1), one possible explanation can be attributed to the decrease in the lactose/Ca$^{2+}$ interactions with the increasing of the temperature; that is, the thermal motion destabilizes the associated lactose/Ca$^{2+}$ structures.

In reality, the CaCl$_2$/lactose/water (Callendar, R., & Leaist, D.G., 2006) system is a ternary one, and the present technique measures changes of the electrical conductance rather than changes of CaCl$_2$ concentration, which are not necessary the same, since changes of the lactose concentration can alter the conductance of the system. Therefore, we really have only measured the main diffusion coefficients ($D_{11}$). However, from the experimental conditions used, we may consider this system as a pseudo-binary one and, consequently, the measured parameters could be taken as the binary diffusion coefficients, $D$.

Assuming that $D$ is a product of both kinetic and thermodynamic factors (equation 2), we suggest that both the thermodynamic factor and the kinetic factor decrease when we
move from a solution of pure CaCl$_2$ to a mixed solution containing both CaCl$_2$ and this carbohydrate. That is,

$$D_{OF} = F_M \times F_T$$  \hspace{1cm} (2)$$

where

$$F_M = \frac{R T}{|z_c| + |z_a|} c$$

$$= (D^0 + \Delta_1 + \Delta_2)$$  \hspace{1cm} (3)$$

and

$$F_T = \left(1 + c \frac{\partial \ln y_\pm}{\partial c}\right)$$  \hspace{1cm} (4)$$

$y_\pm$ represents the thermodynamic activity coefficient of the solute, $D$ is the mutual diffusion coefficient of the electrolyte in m$^2$ s$^{-1}$, $R$ is the gas constant in J mol$^{-1}$ K$^{-1}$, $T$ is the absolute temperature, $z_c$ and $z_a$ are the algebraic valences of the cation and the anion, respectively, and the last term in parenthesis is the activity factor, with $y_\pm$ being the mean molar activity coefficient, $c$ the concentration in mol/m$^3$, and $M$, in mol$^2$ s m$^{-3}$ kg$^{-1}$, is given by
\[
\overline{M} = \frac{1}{N^2 A e_0^2} \left( \frac{\lambda_c^0 \lambda_a^0}{v_a z_a + v_c z_c + z_a^0} \right) c + \Delta M' + \Delta M''
\]  

(5)

In equation 5, the first and second-order electrophoretic terms, are equal to:

\[
\Delta M' = -c \frac{\left( \frac{z_a \lambda_c^0 - z_c \lambda_a^0}{v_c + v_a} \right)^2 \nu v a k}{N_A \left( \frac{z_c \lambda_c^0 + z_a \lambda_a^0}{v_c + v_a} \right)^2 6\pi \eta_0 (1 + ka)}
\]

(6)

and

\[
\Delta M'' = \frac{\left( \frac{z_1 \lambda_1^0 + z_2 \lambda_2^0}{v_1 + v_2} \right)^2}{4\pi^2 \eta_0} \left( \frac{1}{1 + \frac{ka}{\phi(ka)}} \right)
\]

(7)

where \(\eta_0\) is the viscosity of water in N/s/m², \(N_A\) is the Avogadro’s constant, \(e_0\) is the proton charge in coulombs, \(v_c\) and \(v_a\) are the stoichiometric coefficients, \(\lambda_c^0\) and \(\lambda_a^0\) are the limiting molar conductivities of the cation and anion, respectively, in m² mol⁻¹. \(k\) is the ‘reciprocal average radius of ionic atmosphere’ in m⁻¹ (Harned, H.S., & Owen, B.B., 1964), \(a\) is the mean distance of closest approach of ions in m, \(a = 4.0 \times 10^{-10}\) m (Ribeiro, A.C.F., et al., 2008)). The values for \(\phi(ka) = e^{2ka} E_1(2ka)/(1 + ka)\)

have been tabulated by Harned and Owen, and the other letters represent well-known quantities (Harned, H.S., et al., 1964).
Thus, from equation (2) it can be seen that two different effects can control the diffusion process: the ionic mobility ($F_M$) and the gradient of the chemical potential ($F_T$).

Concerning the first effect, and assuming identical considerations than those relative to the effect of the sucrose on the equivalent conductance of KCl (Lobo, V.M.M., & Gonçalves, L.C., 1982), we should accept a decreasing of 6.0 % in the limiting equivalent conductance of CaCl$_2$ in the presence of 0.1 mol dm$^{-3}$ of lactose (3.4 % of lactose) at 25 ºC. That is, it would be $\lambda^0 = 127.70 \times 10^{-4}$ m$^2$ equiv$^{-1}$ Ω$^{-1}$, from which we may assume $\lambda^0_c = 59.50 \times 10^{-4}$ m$^2$ equiv$^{-1}$ Ω$^{-1}$ and $\lambda^0_a = 76.35 \times 10^{-4}$ m$^2$ equiv$^{-1}$ Ω$^{-1}$ at 0.1 M lactose ($\lambda^0_c = 55.93 \times 10^{-4}$ m$^2$ equiv$^{-1}$ Ω$^{-1}$ and $\lambda^0_a = 71.77 \times 10^{-4}$ m$^2$ equiv$^{-1}$ Ω$^{-1}$ in pure water). Considering this value in the Onsager-Fuoss equations (2) to (5), we would get almost identical diffusion coefficients, $D_{OF}$, (Table 2) to that of 0.1 mol dm$^{-3}$ CaCl$_2$ in pure water, within the experimental error (in general, $\Delta D/D$ around 5 %) (Ribeiro, A.C.F., et al., 2008). Therefore, this slight variation of the equivalent conductances relative to pure water solutions cannot be responsible for the significant difference observed for diffusion in the range of concentrations $c \leq 0.1$ mol dm$^{-3}$ of lactose (i.e., $\Delta D/D < -15 \%$). Consequently, assuming that the presence of lactose does not significantly influence the ionic mobility of CaCl$_2$, (confirmed by the very similar $\Delta_1$ values obtained by using limiting equivalent conductances of CaCl$_2$, at both temperatures (Table 3)), we can conclude that the variation in $D$ is mainly due to the variation of $F_T$ (attributed to non-ideal thermodynamic behaviour) (Table 4). In fact, the very small values of $\Delta_1$ obtained for the studied interval of concentrations, lead us to obtain very similar $F_M$ values for the concentration range (< 6.0 %), and so, we can say that the presence of lactose has little effect on $F_M$. 

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From the Onsager-Fuoss equation and our measurements of diffusion coefficients, we have estimated the $F_T$ values at both temperatures (Table 4), within the studied interval of concentrations. Contrarily to the slightly increasing of $F_M$ with concentration, the presence of this carbohydrate leads to a significant decrease of the $F_T$ values, when compared with those estimated for an aqueous system containing only calcium chloride, at 25 ºC (Table 4). Due to the absence of literature values for the parameters necessary to estimate $D_{OF}$ at temperatures other than 25 ºC, it was not possible to make a similar analysis at 37 ºC. Nevertheless, it was possible to infer the temperature effect on the diffusion for this system. Thus, considering our experimental conditions (i.e., dilute solutions), and by assuming that parameters such as viscosity, dielectric constant and hydration in aqueous solutions, as well as complexation, (not taken into account in this model) do not change with concentration, we can conclude that the variation in $D$ is mainly due to the variation of $F_T$ (attributed to non-ideal thermodynamic behaviour). The decreasing of the gradient of the free energy with concentration, $F_T$, for both temperatures, leads us to assume that the eventual presence of solute–solute weak interactions is being responsible by these observations.

4. Conclusions

From the values of $D$ obtained it is possible to conclude that, over the concentration range studied, the diffusion of CaCl$_2$ in aqueous solutions containing lactose at different concentrations appears to be affected by the presence of this sugar. In fact, increasing the lactose concentration in the medium is accompanied by a decrease in the diffusion coefficient values for CaCl$_2$, which is less accentuated at 37 ºC than at 25 ºC. This may be the result of the existence of some association or aggregate formation between Ca$^{2+}$
and lactose. If such interactions exist in this region, they will be observed in two ways: 
(i) a smaller mobility of the CaCl$_2$/lactose aggregates, as a consequence of a steric 
effect; (ii) a significant decreasing of the gradient of the chemical potential with the 
lactose concentration, as a result of the non-ideal thermodynamic behaviour of the 
system. At 37 °C, physiological temperature, this association is the calcium chloride 
plus reduced due to a smaller decrease of both previous effects by the thermal motion. 
Diffusion coefficients for calcium chloride, when obtained in the presence of lactose, 
may provide the transport data necessary to model the diffusion behaviour for various 
chemical and pharmaceutical applications.

Acknowledgments

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CLI/118092/2010 is gratefully acknowledged. One of the authors (A.C.F.R.) is grateful 
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References


Figure 1 – Schematic view of the Lobo’s open-ended capillaries conductimetric cell.

TE and BE are the top and the bottom Pt-electrodes, respectively; ME is the medium Pt-electrode; G is a grid-bulkhead (in perspex); and A is a glass stirrer.
Table 1

Experimental diffusion coefficients, $D$, of aqueous systems containing lactose (1), and CaCl$_2$ (2) at 25 ºC$^a$ (Barros, M.C.F., et al., 2013) and 37 ºC$^a$.

<table>
<thead>
<tr>
<th>$c_1$ / (mol dm$^{-3}$)</th>
<th>$D \pm S_D$ / ($10^{-9}$ m$^2$.s$^{-1}$)</th>
<th>$D \pm S_D$ / ($10^{-9}$ m$^2$.s$^{-1}$)</th>
<th>$(\Delta D/D)_1$ / (%)</th>
<th>$(\Delta D/D)_2$ / (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.200</td>
<td>0.947 ± 0.018</td>
<td>1.343 ± 0.010</td>
<td>-14.7</td>
<td>-6.7</td>
</tr>
<tr>
<td>0.150</td>
<td>1.001 ± 0.019$^e$</td>
<td>1.359 ± 0.019</td>
<td>-9.8</td>
<td>-5.6</td>
</tr>
<tr>
<td>0.100</td>
<td>1.053 ± 0.020</td>
<td>1.372 ± 0.020</td>
<td>-5.1</td>
<td>-4.7</td>
</tr>
<tr>
<td>0.050</td>
<td>1.095 ± 0.021</td>
<td>1.400 ± 0.019</td>
<td>-1.4</td>
<td>-2.8</td>
</tr>
<tr>
<td>0.010</td>
<td>1.111 ± 0.028</td>
<td>1.430 ± 0.026</td>
<td>0.1</td>
<td>-0.7</td>
</tr>
<tr>
<td>0.005</td>
<td>1.112 ± 0.023</td>
<td>1.435 ± 0.020</td>
<td>0.2</td>
<td>-0.3</td>
</tr>
<tr>
<td>0.000</td>
<td>1.094 ± 0.008$^e$</td>
<td>1.454 ± 0.008$^e$</td>
<td>-1.4</td>
<td>1.0</td>
</tr>
</tbody>
</table>
a) Uncertainty, $u(T) = 0.01 \, ^\circ C$. b) Uncertainty, $u(c) = 0.001 \, \text{mol dm}^{-3}$. c) $D$ is the mean diffusion coefficient of 3 experiments and $S_D$ is the standard deviation of that mean. d) $\frac{(\Delta D/D)}{\%}$ represents the deviation between the diffusion coefficients of the system (Lactose + CaCl$_2$ + H$_2$O), $D$, here measured and the diffusion coefficients, $D_{Lib}$, of the system (CaCl$_2$ + H$_2$O) at the indicated temperature (Ribeiro, A.C.F., et al., 2008). e) Interpolated value from data reported in reference (Barros, M.C.F., et al., 2013). f) Extrapolated value (when $c_1 \to 0$) for the diffusion coefficient of aqueous solutions of calcium chloride at $c_2 = 0.100 \, \text{mol dm}^{-3}$ (Barros, M.C.F., et al., 2013). g) Extrapolated value (when $c_1 \to 0$) for the diffusion coefficient of aqueous solutions of calcium chloride at $c_2 = 0.100 \, \text{mol dm}^{-3}$ from the values here obtained at 37 °C.
Table 2

Theoretical diffusion coefficients, $D_{OF}$, of the system (CaCl$_2$ + H$_2$O) at 25 °C, at different concentrations, $c$, using the limiting conductance value of the literature (Robinson, R.A, & Stokes, R.H., 1959) and estimated ones of CaCl$_2$ in aqueous solutions

<table>
<thead>
<tr>
<th>c/mol dm$^{-3}$</th>
<th>$D_{OF}/ \times 10^{-9}$ m$^2$.s$^{-1}$</th>
<th>$D_{OF}/ \times 10^{-9}$ m$^2$.s$^{-1}$</th>
<th>$\Delta D_{OF}/D_{OF}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>($T = 25$ °C)</td>
<td>($T = 25$ °C)</td>
<td>(%)</td>
</tr>
<tr>
<td>0.150</td>
<td>1.180</td>
<td>1.130</td>
<td>-4.2</td>
</tr>
<tr>
<td>0.100</td>
<td>1.184</td>
<td>1.122</td>
<td>-6.2</td>
</tr>
<tr>
<td>0.050</td>
<td>1.182</td>
<td>1.129</td>
<td>-4.4</td>
</tr>
<tr>
<td>0.010</td>
<td>1.213</td>
<td>1.145</td>
<td>-5.9</td>
</tr>
<tr>
<td>0.005</td>
<td>1.233</td>
<td>1.162</td>
<td>-5.7</td>
</tr>
</tbody>
</table>

$^a$ Estimated values by using Onsager-Fuoss equation (3) and the limiting conductance value of CaCl$_2$ in aqueous solutions found in the literature (Robinson, R.A, & Stokes, R.H., 1959) (i.e., $\Lambda^0 = 135.85 \times 10^{-4}$ m$^2$ equiv$^{-1}$ Ω$^{-1}$). $^b$ Estimated values by using Onsager-Fuoss equation (3) and our estimated limiting conductance ($\Lambda^0 = 127.70 \times 10^{-4}$ m$^2$ equiv$^{-1}$ Ω$^{-1}$), calculated from the $\Lambda^0$ value in pure water,
and assuming a drop of 6% in that value in the presence of lactose. \( \frac{\Delta D}{D} \) / % represents the deviation between the diffusion coefficients obtained by using the Onsager-Fuoss equation (2) and the limiting conductance value in the literature (Robinson, R.A, & Stokes, R.H., 1959), and those obtained by the same model, but using our estimated limiting conductance of CaCl\(_2\) in aqueous solutions, at the indicated temperature.
Table 3

Electrophoretic factors, $\Delta_1 + \Delta_2$, estimated from equation (3) at 25 ºC and 37 ºC for aqueous lactose (1) + CaCl$_2$ (2) solutions

<table>
<thead>
<tr>
<th>$c_1$/mol dm$^{-3}$</th>
<th>$(\Delta_1 + \Delta_2)/10^9$ m$^2$ s$^{-1}$ a)</th>
<th>$\Delta(\Delta_1 + \Delta_2)/(\Delta_1 + \Delta_2)$ % b)</th>
<th>$(\Delta_1 + \Delta_2)/10^9$ m$^2$ s$^{-1}$ c)</th>
<th>$\Delta(\Delta_1 + \Delta_2)/(\Delta_1 + \Delta_2)$ % d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.200</td>
<td>0.186</td>
<td>-0.5</td>
<td>0.184</td>
<td>-2.8</td>
</tr>
<tr>
<td>0.150</td>
<td>0.142</td>
<td>-0.7</td>
<td>0.152</td>
<td>2.8</td>
</tr>
<tr>
<td>0.100</td>
<td>0.156</td>
<td>-0.6</td>
<td>0.154</td>
<td>-2.9</td>
</tr>
<tr>
<td>0.050</td>
<td>0.137</td>
<td>0.7</td>
<td>0.136</td>
<td>-2.9</td>
</tr>
<tr>
<td>0.010</td>
<td>0.067</td>
<td>0.0</td>
<td>0.067</td>
<td>-2.9</td>
</tr>
<tr>
<td>0.005</td>
<td>0.044</td>
<td>0.0</td>
<td>0.044</td>
<td>-0.5</td>
</tr>
<tr>
<td>0.000</td>
<td>0.000</td>
<td>0.0</td>
<td>0.000</td>
<td>0.0</td>
</tr>
</tbody>
</table>

a) Calculated values by using the Onsager-Fuoss equation (3) and our estimated limiting conductance value of CaCl$_2$ in aqueous solutions containing lactose at 25 ºC ($\Lambda^0 = 127.70 \times 10^{-4}$ m$^2$ equiv$^{-1}$ Ω$^{-1}$). b) $\Delta(\Delta_1 + \Delta_2)/(\Delta_1 + \Delta_2)$ % represents the deviation between the electrophoretic factors obtained by using the Onsager-Fuoss equation (3) and our estimated value $\Lambda^0 = 127.70 \times 10^{-4}$.
m² equiv⁻¹ Ω⁻¹, and those obtained by the same model, but using the limiting conductance value found in the literature (Robinson, R.A, & Stokes, R.H., 1959) (Λ₀ = 135.85 x 10⁻⁴ m² equiv⁻¹ Ω⁻¹), at 25 °C.  

Estimates values by using the Onsager-Fuoss equation (3) and our estimated limiting conductance value of CaCl₂ in aqueous solutions containing lactose (Λ₀ = 161.91 x 10⁻⁴ m² equiv⁻¹ Ω⁻¹), calculated from the Λ₀ value in pure water, and assuming a value drop of 6 % in the presence of lactose. 

Δ(Δ₁ + Δ₂)/ (Δ₁ + Δ₂) % represent the deviation between the electrophoretic factors obtained by using the Onsager-Fuoss equation (3) and our estimated value (Λ₀ = 161.91 x 10⁻⁴ m² equiv⁻¹ Ω⁻¹), and those obtained by the same model, but using the limiting conductance value found in the literature (Robinson, R.A, & Stokes, R.H., 1959) ((Λ₀ = 172.24 x 10⁻⁴ m² equiv⁻¹ Ω⁻¹), at 37 °C.
Table 4

Thermodynamic factors, $F_T$, for lactose (1) + CaCl$_2$ (2) aqueous solutions estimated from our experimental values of $D$ and from equation (2), at 25 ºC and 37 ºC.

<table>
<thead>
<tr>
<th>$c_1$/mol dm$^{-3}$</th>
<th>$F_T$ (T = 25 ºC)</th>
<th>$\Delta F_T/F_T$% $^a$ (T = 25 ºC)</th>
<th>$\Delta F_T/F_T$% $^b$ (T = 25 ºC)</th>
<th>$F_T$ (T = 37 ºC)</th>
<th>$\Delta F_T/F_T$% $^c$ (T = 37 ºC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.200</td>
<td>0.657</td>
<td>5.6</td>
<td>-18.0</td>
<td>0.754</td>
<td>5.7</td>
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<tr>
<td>0.150</td>
<td>0.748</td>
<td>4.2</td>
<td>-6.0</td>
<td>0.777</td>
<td>5.7</td>
</tr>
<tr>
<td>0.100</td>
<td>0.776</td>
<td>4.7</td>
<td>-2.4</td>
<td>0.784</td>
<td>5.9</td>
</tr>
<tr>
<td>0.050</td>
<td>0.794</td>
<td>5.6</td>
<td>-1.5</td>
<td>0.808</td>
<td>5.9</td>
</tr>
<tr>
<td>0.010</td>
<td>0.840</td>
<td>6.0</td>
<td>-3.0</td>
<td>0.860</td>
<td>6.0</td>
</tr>
<tr>
<td>0.005</td>
<td>0.855</td>
<td>5.8</td>
<td>-4.3</td>
<td>0.875</td>
<td>6.2</td>
</tr>
<tr>
<td>0.000</td>
<td>1.000</td>
<td>0.0</td>
<td>1.0</td>
<td>1.000</td>
<td>0.0</td>
</tr>
</tbody>
</table>

$^a$ $\Delta F_T/F_T$% represents the deviation between the thermodynamic factors estimated from our experimental values of $D$ and from equation (2) at 25 ºC, by using our estimated values $\kappa_c^0 = 55.93 \times 10^{-4}$ m$^2$ equiv$^{-1}$ Ω$^{-1}$ and $\kappa_a^0 = 71.77 \times 10^{-4}$.
m² equiv⁻¹ Ω⁻¹ and the corresponding values found in the literature (Robinson, R.A, & Stokes, R.H., 1959), i.e., \( \lambda_c^0 = 59.50 \times 10^{-4} \) m² equiv⁻¹ Ω⁻¹ and \( \lambda_a^0 = 76.35 \times 10^{-4} \) m² equiv⁻¹ Ω⁻¹. b) \( \Delta F_T / F_T \% \) represents the deviation between the thermodynamic factors estimated from our experimental values of \( D \) and from equation (2), at 25 °C and by using our estimated values \( \lambda_c^0 = 55.93 \times 10^{-4} \) m² equiv⁻¹ Ω⁻¹ and \( \lambda_a^0 = 71.77 \times 10^{-4} \) m² equiv⁻¹ Ω⁻¹, and those found in the literature (Robinson, R.A, & Stokes, R.H., 1959). c) \( \Delta F_T / F_T \% \) represents the deviation between the thermodynamic factors estimated from our experimental values of \( D \) and from equation (2) at 37 °C, by using our estimated values \( \lambda_c^0 = 71.91 \times 10^{-4} \) m² equiv⁻¹ Ω⁻¹ and \( \lambda_a^0 = 90.00 \times 10^{-4} \) m² equiv⁻¹ Ω⁻¹ and the values from the literature (Robinson, R.A, & Stokes, R.H., 1959), i.e., \( \lambda_c^0 = 76.50 \times 10^{-4} \) m² equiv⁻¹ Ω⁻¹ and \( \lambda_a^0 = 95.74 \times 10^{-4} \) m² equiv⁻¹ Ω⁻¹.
Research Highlights

- Calcium transport in lactose/calcium systems at 37 °C is affected by sugar concentration

- Association calcium/lactose is responsible of decreasing in diffusion coefficient values

- At 37 °C, the thermal motion difficult the stabilization of associated structures