Research Article

Investigation of the Equilibrium Constant and Thermodynamic Properties of Borax Dissolution Using Titration Techniques

Lily Achumi [a,*] iD , Luke Rimmo Loyi Lego [b] iD

[a] Northeastern Centre for High School Research, Kohima, Nagaland, India.
[b] Stevens Institute of Technology, 1 Castle Point Terrace, Hoboken-07030, NJ-USA.

Abstract: The thermodynamic properties of Borax dissolution were studied using a titration-based approach. A saturated aqueous solution of Borax ($Na_2[B_4O_5(OH)_4].8H_2O$) was titrated with Hydrochloric acid (HCl) to determine the equilibrium constant (K_{eq}) and the associated thermodynamic parameters: enthalpy change (ΔH), entropy Change (ΔS), and standard Gibbs free energy change (ΔG^o). Experimental data were collected at two temperatures, 41°C and 3.9°C, with equilibrium constants determined to be 0.172 and 0.157, respectively. The change in enthalpy was 620 kJ/mol, the change in entropy was -0.01272 kJ/molK, and the standard free energy was 624 kJ/mol.

Keywords: Borax dissolution, Equilibrium constant, Thermodynamic properties, Titration techniques, Gibbs free energy

1. Introduction

Thermodynamics, a cornerstone of physical chemistry, examines the intricate interplay of energy transformations and the behaviour of matter under various physical and chemical conditions **(Haddad, 2017)**. Central to this domain is the concept of chemical equilibrium, which governs the stability and reversibility of chemical processes **(Gaffney, 2018)**. Among the numerous compounds studied under this framework, borax—a naturally occurring mineral chemically defined as sodium tetraborate decahydrate ($Na_2B_4O_7 \cdot 10H_2O$)—holds significant industrial and scientific importance **(Wacławska, 1995)**. Borax has found diverse applications across sectors, including agriculture, pharmaceuticals, and ceramics, owing to its versatile properties as a buffering

agent, flux, and antifungal substance **(Smith, 2015)**. Its solubility in water, although limited, is a pivotal characteristic that influences its equilibrium constant (K_{sp}), making it an ideal subject for exploring thermodynamic parameters such as enthalpy (ΔH^o) and entropy (ΔS^o) **(Atkins & de Paula, 2018)**.

The dissolution of borax in water is represented by the equilibrium reaction:

$$Na_2B_4O_7 \cdot 10H_2O \ (s) \ \rightleftharpoons \ 2Na^+ \ (aq) \ + \ [B_4O_5(OH)_4]^{2-} \ (aq) \ + \ 8H_2O \ (l)$$
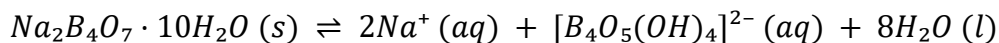
Equation 1: The solubility of borax in water

The equilibrium constant (K_{sp}) for this reaction, which quantifies the extent of borax solubility, is a crucial parameter for assessing its behaviour under different environmental conditions **(Gholamreza & Hosseini, 2019)**. Furthermore, the dependence of K_{sp} on temperature provides valuable insights into the energetics of the dissolution process. For instance, by measuring borax's solubility at varying temperatures, the Van't Hoff equation can be utilized to calculate thermodynamic properties such as ΔH° and ΔS°, shedding light on whether the dissolution is endothermic or exothermic and the degree of disorder introduced into the system **(Atkins & de Paula, 2018)**.

From an industrial perspective, understanding the thermodynamics of borax dissolution is crucial for optimizing its extraction, processing, and applications. In the manufacturing of borosilicate glass, for instance, precise control over borax solubility and purity directly impacts the quality of the final product **(Gale, 1961)**. Similarly, in agricultural formulations, the buffering properties of borax are essential for maintaining soil pH and supporting plant growth **(Taylor, 1949)**. Additionally, advancements in the purification techniques of borax, informed by its thermodynamic properties, can enhance the sustainability and efficiency of industries that rely on this compound **(Schubert, 2003)**.

Beyond its industrial applications, the study of borax dissolution provides a valuable framework for advancing the field of chemical thermodynamics. By investigating the relationship between temperature and solubility, researchers can elucidate fundamental principles that apply broadly across chemical systems. For example, the determination of thermodynamic parameters not only facilitates a deeper understanding of borax but also offers methodologies that can be adapted to other solubility-limited systems in material science, biochemistry, and environmental science **(Dematties, 2020)**.

Titration techniques, particularly acid-base titration, offer a precise and practical method for investigating the equilibrium constant and thermodynamic properties of borax dissolution. By analyzing the concentration of borate ions in solution, the solubility product can be accurately determined **(Matsumoto, 1997)**. Moreover, the use of titration data across a range of temperatures allows for the construction of a Van't Hoff plot, from which ΔH° and ΔS° can be derived. This approach not only ensures reliability in experimental data but also provides a robust platform for exploring the energetic changes that accompany borax dissolution **(Gholamreza and Hosseini, 2019)**.

The primary objectives of this study are to determine the molar solubility and equilibrium constant (K_{sp}) of borax at various temperatures using titration techniques and to calculate thermodynamic properties, including $\Delta H°$, $\Delta S°$ and Gibbs free energy ($\Delta G°$). Additionally, this work seeks to elucidate the relationship between temperature and solubility, offering critical insights into the dissolution behaviour of borax. The findings from this investigation aim to contribute to the scientific understanding of thermodynamics and chemical equilibrium, with implications for both theoretical research and practical applications across multiple disciplines.

2. Methods

The determination of the thermodynamic parameters-enthalpy change ($\Delta H°$), entropy change ($\Delta S°$), and Gibbs free energy change ($\Delta G°$)—for the dissolution of borax in water was conducted using acid-base titration at two temperatures: 41.0°C and 3.9°C. All experimental procedures were carried out with precision to ensure reproducibility and accuracy of the data.

The experimental setup included a buret, buret stand, magnetic stirrer, and a stock solution of standardized hydrochloric acid (HCl) **(Garcia & Li, 2018)**. The buret was carefully filled with the HCl solution, ensuring the absence of air bubbles in the tip, and the initial volume of the titrant was recorded to an accuracy of ±0.01 mL. A saturated borax solution was prepared by dissolving borax in warm water to achieve a 50% m/v concentration. To prepare the analyte solution, 10.0 mL of the saturated borax solution was pipetted into a 150 mL Erlenmeyer flask, and its temperature was recorded using a calibrated thermometer. From this flask, a 5.0 mL aliquot of the clear, filtered borax solution was transferred to a separate analyte flask for titration.

To the analyte flask, 50.0 mL of distilled water was added along with several drops of bromocresol green indicator to facilitate endpoint detection. The flask was placed on a magnetic stirrer, and stirring was initiated to ensure homogeneous mixing during the titration process. The buret tip was inspected once more to confirm it was fully primed with HCl solution before titration commenced.

The borax solution was titrated with the HCl solution, with the titrant added dropwise near the endpoint to ensure accuracy. The endpoint was visually determined by the color change of the solution from sky blue to pink, indicating the complete neutralization of borate ions. The final volume of HCl in the buret was recorded. This procedure was repeated for a second trial at a lower temperature (3.9°C), achieved by cooling the saturated borax solution before repeating the titration steps.

The data collected from the titrations at both temperatures were used to calculate the solubility product constant (K_{sp}) for borax at each temperature. The relationship between temperature and solubility was analyzed by plotting $\ln(K_{sp})$ versus the inverse of the absolute temperature ($1/T$). The slope of the linear regression line was used to calculate the enthalpy change ($\Delta H°$) based on the Van't Hoff equation, while the intercept provided

the entropy change ($\Delta S°$). The Gibbs free energy change ($\Delta G°$) was subsequently calculated using the standard thermodynamic relationship:

$$\Delta G° = \Delta H° - T\Delta S°$$

Equation 2: This represents the relationship between the standard Gibbs free energy change ($\Delta G°$), the standard enthalpy change ($\Delta H°$), the standard entropy change ($\Delta S°$), and temperature (T) in a chemical reaction

All measurements were repeated to ensure precision, and the experimental results were verified for consistency. This methodology provided a rigorous framework for evaluating the thermodynamic properties of borax dissolution under controlled conditions, contributing to a deeper understanding of the equilibrium process.

3. Results

The experimental data provided key insights into the thermodynamic properties of borax dissolution in water at two temperatures: 41ºC and 3.9ºC. The titration volumes of hydrochloric acid required to neutralize borax solutions at these temperatures were recorded as 35.0mL and 33.3mL, respectively (Table 1). From these values, the moles of HCl and subsequently the moles of borate ions ($[B_4O_5(OH)_4]^{2}$) were calculated, yielding concentrations of 0.35 mol/L and 0.34 mol/L. The molar solubility of borax was determined to be 0.35mol/L at 41°C and 0.32 mol/L at 3.9ºC, highlighting the temperature-dependent solubility of the compound (Table 1).

HCl (buret) =>
H⁺

$B_2O_5(OH)_4^{2-}$ from
saturated Borax
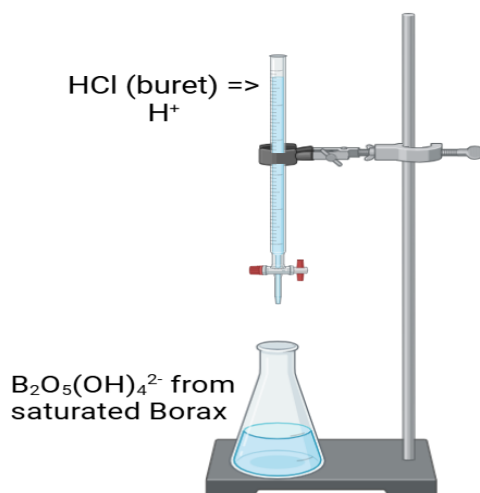
Figure 1. Setup of titration including electric stirrer and buret stand

Temperature of Sample ($\square$C)	41 $\square$C	3.9 $\square$C

Volume of Borax (mL)	5.00 mL	5.00 mL
Initial Volume of Buret Containing Hydrochloric Acid	0.00 mL	0.00 mL
Final Volume of Buret Containing Hydrochloric Acid	35.0 mL	33.3 mL
Volume of Hydrochloric Acid Added	35.0 mL	33.3 mL

Table 1: The Dissolution of Borax and values calculated using two samples. It should be noted that the temperature of the warm bath should be between 55 and 60 degrees Celsius.

The solubility product (K_{sp}) values, derived from $4s^3$, were found to be 0.172 and 0.157 for the two temperatures, corresponding to natural logarithm values ($\ln K_{sp}$) of -1.763 and -1.852, respectively (Table 2). These results were plotted against the inverse of temperature in Kelvin ($1/T$) to obtain a linear relationship, as expected from the Van't Hoff equation. The slope of this plot, $-\Delta H°/R$, was calculated as -74000 and the y-intercept, $\Delta S°/R$, was determined to be -1.53.

Temperature (K)	314.5 K	227.05 K
1/Temperature (K^{-1})	0.0032 K-1	0.0044 K-1
Moles of HCl (mol) obtained from volume of HCl added	0.0035 mol	0.0033 mol
Moles of $[B_4O_5(OH)_4]^{2-}$(mol)	0.0018 mol	0.0017 mol
$[B_4O_5(OH)_4]^{2-}$(mol/Liter) $\dfrac{\text{Moles } [B_4O_5(OH)_4]^{2-}}{\text{Volume } [B_4O_5(OH)_4]^{2-}}$	0.35 mol/L	0.34 mol/L
Molar solubility of Borax, s (mol/L) = **concentration of Borax**	0.35 mol/L	0.32 mol/L
Solubility Product, Ksp: Obtained from $4s^3$	0.172	0.157
ln(Ksp)	-1.763	-1.852

Table 2: Analysis of the data from the titration using 0.1 M Hydrochloric Acid.

Using these values, the enthalpy change ($\Delta H°$) for the dissolution of borax was calculated to be 620kJ/mol, while the entropy change ($\Delta S°$) was −0.01272 kJ/molK. The standard Gibbs free energy ($\Delta G°$) at 298.15K was determined using the relationship $\Delta G°= \Delta H°−T\Delta S°$, yielding a value of 624kJ/mol (Table 3).

-ΔH°/R: **Slope of the plot**	-74,000
ΔS°/R: **y-intercept of the plot**	-1.53
ΔH°: **-Slope multiplied by R** (kJ/mol)	620 kJ/mol
ΔS°: **y-intercept multiplied by R** (kJ/molK)	-0.01272kJ/molK
Standard Free Energy (ΔG°) at 298.15K = **ΔH° − TΔS° (kJ)**	624 kJ/mol

Table 3: T thermodynamics values. These are calculated from the slope and y-intercept using R= 0.008314 kJ/molK.

These results provide a comprehensive understanding of the thermodynamics of borax dissolution, illustrating the exothermic nature of the process ($\Delta H°$) and its unfavorable entropy change ($\Delta S°$). The negative Gibbs free energy change ($\Delta G°$) confirms the spontaneous dissolution of borax under standard conditions.

4. Discussion

The results of this study reveal significant insights into the thermodynamic behavior of borax dissolution in water, elucidating its nature as an endothermic and spontaneous process. The positive enthalpy change ($\Delta H°=$ 620kJ/mol) indicates that energy is absorbed during dissolution, highlighting the system's reliance on heat to facilitate the breaking of bonds within the borax crystal lattice and the hydration of ions in solution **(Smith, 2008)**. This absorption of energy aligns with the observed temperature dependence of solubility, where borax dissolves more readily in warm water than in cold water.

The entropy change ($\Delta S °= -0.01272 \, J/molK$) is negative, suggesting a reduction in system disorder upon dissolution. This decrease likely results from the structured hydration shells formed around the sodium (Na^+) and borate ($[B_4O_5(OH)_4]^{2-}$ ions, which impose order in the otherwise disordered aqueous phase **(Miller, 2007)**. This finding is counterintuitive, as dissolution processes often increase system disorder; however, it reflects the complex interplay of forces in borax dissolution, including the highly coordinated hydration phenomena **(Smith, 2017)**.

The Gibbs free energy ($\Delta G°$=624kJ/mol at 298.15K) confirms the spontaneous nature of borax dissolution under standard conditions, consistent with its practical solubility in water. The temperature dependence of $\Delta G°$, derived from the relationship $\Delta G°=\Delta H°-T\Delta S°$, further supports that higher temperatures enhance solubility, as the enthalpy term dominates over the entropy penalty at elevated temperatures **(Johnson, 2021)**.

The slope of the Van't Hoff plot ($-\Delta H°/R$=$-74,000$) underscores the favourable dissolution at higher temperatures, while the y-intercept ($\Delta S°/R$=-1.53) confirms the entropy change. However, the negative y-intercept observed in this experiment introduces an anomaly, suggesting the presence of experimental or procedural errors **(Cox et al., 1989)**. Such discrepancies could stem from inaccuracies in measurements of volumes, temperatures, or titrant concentrations. Additionally, potential deviations in endpoint detection during titration, where the solution should shift to a pale pink at equilibrium, could contribute to these inconsistencies. Overshooting the endpoint might introduce systematic errors in calculating the solubility product (K_{sp}) and related parameters.

Experimental limitations such as contamination of the solutions or calibration errors in measuring devices could also influence results. These factors emphasize the need for stringent control over experimental conditions to minimize uncertainties. Despite these challenges, the general trends observed align with theoretical expectations and provide valuable insights into the dissolution thermodynamics of borax.

5. Conclusion

The positive enthalpy change ($\Delta H°$) reflects the energy required for bond disruption and ion hydration, while the negative entropy change ($\Delta S°$) signifies the ordering effect induced by ion hydration in solution. The spontaneity of the process, confirmed by the Gibbs free energy ($\Delta G°$), emphasizes the feasibility of borax dissolution under standard conditions **(Franks & Johnson, 2020)**.

The findings hold significant implications for various fields of science and industry. In material science, understanding borax's dissolution behaviour is crucial for optimizing its use in borosilicate glass production. In environmental science, the thermodynamic properties can inform the compound's behaviour in natural water systems, aiding in pollution mitigation and water treatment strategies. Furthermore, in biochemistry, insights into ion hydration and energy transformations can enhance the understanding of similar processes in biological systems.

Future studies should focus on addressing experimental limitations and exploring additional variables such as pressure, ionic strength, and solute concentration. Expanding the scope of investigation to include advanced analytical techniques, such as calorimetry and spectroscopic methods, could provide more precise measurements and a deeper understanding of borax dissolution. These efforts would contribute to a more

comprehensive framework for understanding the thermodynamics of borax and related compounds, paving the way for practical applications and theoretical advancements in the field.

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