Lab Exp. 9: Identification of an Unknown Weak Acid

MARK REJNA

University of California, Berkeley

ABSTRACT: The identification of unknown weak acids is essential in many scientific fields making fundamental techniques of titrations of interest. In this investigation, the titration of unknown weak acid ID:#66 was used to determine the identity of the weak acid. A dilute solution of sodium hydroxide (NaOH) was prepared and as standardised using potassium hydrogen phthalate (KHP). A solution of the unknown acid was then titrated with the NaOH solution. A pH probe and LabQuest2 interface were used to find a pH curve which was then analysed using the derivative method and the Gran plot method to find the Ka and relative molecular mass of the unknown acid. The calculated value of Ka was determined to be 1.36E-5 ± 1.19E-6 and that of M_r was determined to be 155 ± 30.2 g/mol. However, the unknown acid was later revealed to be potassium bitartrate ($KC_4H_5O_6$) which has literature values of Ka of 3.98E-5 and a M_r of 188.177.

I. INTRODUCTION

In this investigation the unknown weak acid will be identified using an acid-base titration. In an acid-base titration a solution of known concentration is carefully added to a sample of unknown concentration until the sample is neutralised. If the sample is acidic, then the titrant must be basic, and vice versa. In acid-base titrations an indicator is added to the sample which indicates when the sample has reached an equivalence point by a change in colour. By recording the volume of titrant added to the sample and the pH of the sample throughout the titration, the concentration and equivalence point of the sample can be determined.

There are four different types of acid-base titrations: strong acid and strong base, strong acid and weak base, weak acid and strong base, and weak acid and weak base. When both a strong acid and strong base are titrated together, the resulting equivalence point is neutral at pH 7. In contrast, when titrating a strong acid and a weak base or vice versa the equivalence point is greater than or less than pH 7 respectively. In these titrations a buffer solution is temporarily formed. A point of half-equivalence can be found within the buffer region at exactly half the volume of the equivalence point as seen in *Figure 0*. At the half-equivalence point the pH of the buffer is equal to its pKa. The titration of a weak acid and a weak base has an equivalence point dependent on the solutions, but it does not form a buffer region.

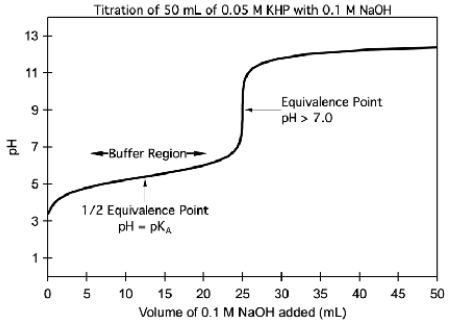

Figure 0: Titration curves of WA+SB and SA+WB[1]

In this investigation an unknown weak acid was titrated with sodium hydroxide (NaOH). Therefore, a titration of a weak acid with a strong base occurs. An appropriate indicator is used to indicate the equivalence point, in this case the chosen indicator was phenolphthalein. Phenolphthalein indicates equivalence points in the pH range of 8.2-10.0.[2] Phenolphthalein is colourless in acidic solutions and turns pink in basic solutions. Therefore, the titration was completed when the colour of the sample turned pink.

In Table 1 is a list of the possible unknown weak acids along with their literature values. The aim of this identify the unknown acid by calculating a Ka and relative molecular mass which corresponding to one of the acids listed.

Table 1: Possible unknown acids with literature values[1]

Acid	Ka	M_r (g/mol)
Mandelic acid	3.89E-4	152.147
3-hydroxybenzoic acid	8.32E-5	138.120
Benzoic acid	6.31E-5	122.120
Potassium bitartrate	3.98E-5	188.177
4-aminobenzoic acid	1.62E-5	137.140
Nicotinic acid	1.41E-5	123.109

II. METHODOLOGY

Part 1: Preparing a standardised sodium hydroxide (NaOH) solution using potassium hydrogen phthalate (KHP)

A beaker was filled with 500 ml of distilled water and boiled on a hotplate for approximately 5 minutes in order to remove dissolved gasses such as nitrogen and carbon dioxide. The beaker containing distilled water was then allowed to cool in a water bath until the degassed distilled water reached a temperature of less than 30 °C. The cool, degassed distilled water was then transferred into a clean plastic (HDPE) bottle. Approximately 10 ml of 6 M sodium hydroxide was transferred into the plastic bottle to form a ~510 ml NaOH solution of ~0.1 M. A 50 ml burette was set-up and rinsed with the ~0.1 M NaOH solution in order to clean it and remove air bubbles from the tip of the burette. Approximately 0.4 grams of KHP was weighed and transferred into an Erlenmeyer flask. 50 ml of distilled water and 5 drops of phenolphthalein indicator was added to the flask. The flask was then swirled until the solid KHP fully dissolved in the distilled water. The burette was then filled with the ~0.1 M NaOH solution. The initial burette volume was recorded. KHP solution was then carefully titrated until the solution turned a faint pink colour which remained persistent after swirling (white paper was placed under the Erlenmeyer flask to better see the colour change). The final burette volume was recorded. This titration process was repeated 2 more times. The precise concentration of the diluted NaOH was calculated and labelled on the bottle. The bottle was stored for two weeks until the next lab session.[1]

Part 2: Unknown acid titrations using standardised NaOH solution

A LabQuest2 interface was connected to a pH probe and the pH probe was calibrated using buffers with a pH of 4, 7, and 10. Between each usage the pH probe was washed thoroughly with distilled water and stored in its designated storage bottle. A new clean 50 ml burette was set-up and rinsed with the NaOH solution stored from *Part 1* in order to further clean it and remove air bubbles from the tip of the burette. A preliminary trial was conducted first in which a mass of between 0.1 and 0.2 grams of unknown acid was measured and transferred into a 250 ml Erlenmeyer flask. The precise mass of unknown acid was recorded. 100 ml and 5 drops of phenolphthalein indicator were then added to the flask. The flask was then swirled until the majority of the unknown acid had dissolved. The initial burette volume was recorded. The NaOH Solution was used to roughly titrated the unknown acid solution until it turned a faint pink colour which remained persistent after swirling. Again white paper was placed under the Erlenmeyer flask to better see the colour change. The final burette volume was recorded and an approximate molar mass was calculated. Furthermore the preliminary trial allowed the estimate of how much unknown acid will be required for a volume of 30 ± 5 ml NaOH solution to neutralise it. After the preliminary trials, the main trails were set-up with the mass of unknown acid diluted in 100 ml of water and 5 drops of phenolphthalein indicator in the Erlenmeyer flask along with a magnetic stir bar and the pH probe. The flask was positioned on top of a magnetic stirring plate and under the burette where all of the components inside the flask were functional. The magnetic stir plate was turned on at a slow speed as to not cause splashes or bubbles but simultaneously, sufficiently mix the solution. The initial pH at 0 ml was recorded on the LabQuest2. Frequently throughout the titration, pH and volume measurements were recorded on the LabQuest2, enough values were acquired to thoroughly plot the titration curve. Two more titrations were carried out in the same manner. The pH probe was cleaned with distilled water between each trial. After all data was collected, data was exported from the LabQuest2 interface.[1]

III. DATA ANALYSIS

It should be noted that example calculations for trial 1 are provided for further understanding on how the values were acquired. All calculations are calculated using Excel and

Part 1: Standardised sodium hydroxide solution

Data collected in *Part 1* of the investigation can be found in *Table 2*.

Table 2: Data of KHP titrated by NaOH

Trial	m of KHP (g)	n of KHP (mol)	Starting V of NaOH (ml)	Final V of NaOH (ml)	V of NaOH used (ml)	c of NaOH (M)
1	0.4006	1.96E-03	10.20	27.50	17.30	0.113
2	0.4006	1.96E-03	9.40	26.40	17.00	0.115
3	0.4000	1.96E-03	27.60	44.60	17.00	0.115

The number of moles of KHP can be calculated using the following equation: $n = \frac{m}{M_r}$ (1)

$n = \frac{0.4006}{204.22} \approx 0.00196\ mol$. The concentration of NaOH can be calculated using the following equation: $c = \frac{n}{V}$ (2)

$c = \frac{0.00196}{(27.5-10.2)\cdot 10^{-3}} \approx 0.113\ M$. The mean concentration of NaOH can be calculated as $\overline{c} = \frac{0.113+2\cdot 0.115}{3} \approx 0.114\ M$ and the standard deviation can be calculated as $s = \sqrt{\frac{(0.113-0.114)^2+2\cdot(0.115-0.114)^2}{2}} \approx 0.00111$. Finally, the 95% confidence interval can be calculated using the following formula: $CI = \frac{t\cdot s}{\sqrt{N}}$ (3) where the t is the t-score and is equal to 4.304 for 3 data points. The 95% confidence interval for the mean concentration of NaOH is: $CI = \frac{4.304\cdot 0.00111}{\sqrt{3}} \approx 0.00276\ M$. Therefore the concentration of NaOH including uncertainty can be written as **0.114 ± 2.76E-3 M.**

Table 3: Confidence interval for concentration of NaOH

Mean c of NaOH (M)	Standard deviation of c of NaOH	95% confidence interval for mean concentration of NaOH (M)
0.114	0.00111	± 0.00276

Part 2: Unknown acid titration using NaOH solution

Data collected from the three titrations of the unknown acid with NaOH solution in *Part 2* of the investigation can be found in *Tables 4, 5, and 6* in the *APPENDIX*. The forward difference of the finite difference method was used to find the points for the first and second derivatives. The following formulas were used[3]: $f'(x_i) = \frac{f(x_{i+1})-f(x_i)}{x_{i+1}-x_i}$ (4) and $f''(x_i) = \frac{f'(x_{i+1})-f'(x_i)}{x_{i+1}-x_i}$ (5). The data can be analysed more effectively visually, *figures 1, 2, and 3* represent the raw data for titration 1, the first derivative for titration 1, and the second derivative for titration 1. The figures for titrations 2 and 3 can be found in the *APPENDIX*.

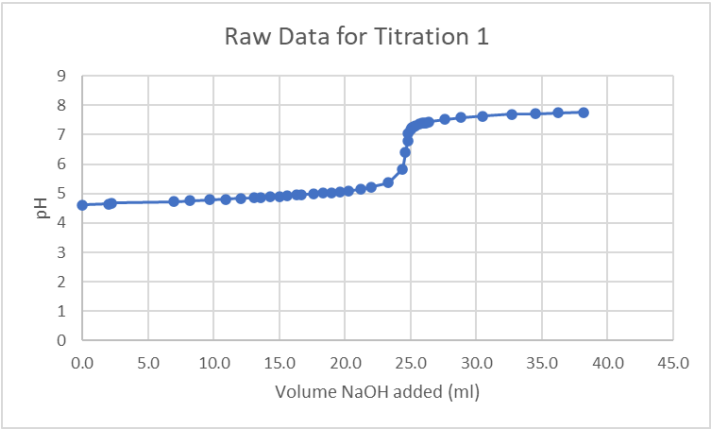

Figure 1: Raw data for titration 1 (pH curve)

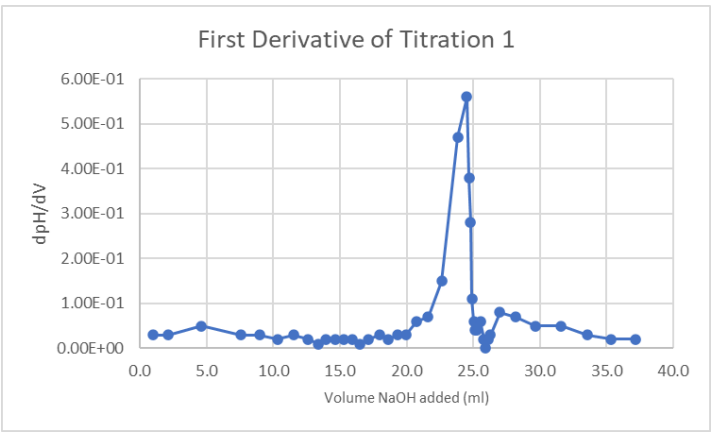

Figure 2: First derivative of titration 1

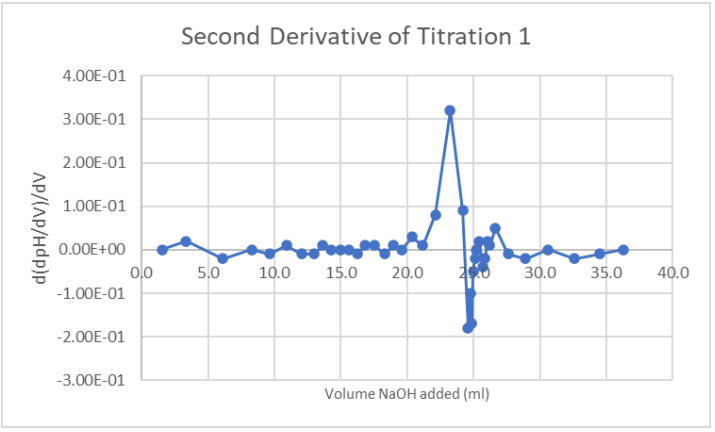

Figure 3: Second derivative of titration 1

The equivalence point of the titration is difficult to see in *Figure 1* as it is a point of inflection; however, in *Figure 2* the equivalence point can be seen as the local maximum and in *Figure 3* the equivalence point is represented by a zero point (most accurate estimation). The half-equivalence point can be determined as it is half the volume at the equivalence point. The following table shows the volumes at equivalence (zero points) and half-equivalence points in all titrations.

Table 7: Volume at equivalence and half-equivalence

Titration	Volume at equivalence point (zero point for second derivative) (ml)	Volume at half-equivalence (ml)
1	24.5	12.25
2	21.0	10.50
3	23.0	11.50

At the half-equivalence point pH is equal to pKa. The Ka of the unknown acid can be calculated as demonstrated: $Ka = 10^{-pKa}$ (6) $Ka = 10^{-4.85} \approx 1.41 \cdot 10^{-5}$.

Table 8: Volume at equivalence and half-equivalence

pH at half-equivalence	pKa of unknown acid	Ka of unknown acid
4.85	4.85	1.41E-5
4.88	4.88	1.32E-5
4.87	4.87	1.35E-5

The mean ka of the unknown acid can be calculated as $\overline{Ka} = \frac{(1.41+1.32+1.35)\cdot 10^{-5}}{3} \approx 1.36 \cdot 10^{-5}$ and the standard deviation can be calculated as above to give $s \approx 4.81 \cdot 10^{-7}$. Finally, the 95% confidence interval can be calculated using formula (3). The 95% confidence interval for the Ka of the unknown acid is: $CI = \frac{4.304 \cdot 4.81 \cdot 10^{-7}}{\sqrt{3}} \approx 1.19 \cdot 10^{-6}$. Therefore the ka of the unknown acid including uncertainty can be written as **1.36E-5 ± 1.19E-6.**

Table 9: Confidence interval for Ka of unknown acid

Mean Ka of unknown acid	Standard deviation of Ka of unknown acid	95% confidence interval for mean Ka of unknown acid
1.36E-5	4.81E-7	± 1.19E-6

Furthermore the relative molecular mass of the unknown acid can be determined using the volume of NaOH solution at the end point. The volume at the end point is the volume needed to neutralise the unknown acid, i.e. the equivalence point. By using a derivation of equation (2) the number of moles of unknown acid can be found $n = 0.114 \cdot 24.5 \cdot 10^{-3} \approx 0.00278\ mol$. By using a derivation of equation (1) the relative molecular mass can be calculated $M_r = \frac{0.4006}{0.00278} \approx 144.018\ \frac{g}{mol}$.

Table 10: Relative molecular mass of unknown acid

Titration	V at end point (ml)	n of unknown acid (mol)	Relative molecular mass of unknown acid (g/mol)
1	24.5	2.78E-3	144.018
2	21.0	2.38E-3	168.136
3	23.0	3.61E-3	153.221

The mean relative molecular mass of the unknown acid can be found as $\overline{M_r} = \frac{144.018+168.136+153.221}{3} \approx 155\ \frac{g}{mol}$ and the standard deviation can be calculated as above to give $s \approx 12.2$. The 95% confidence interval can be calculated using formula (3). The 95% confidence interval for the M_r of the unknown acid is: $CI = \frac{4.304 \cdot 12.2}{\sqrt{3}} \approx 30.2$. Therefore the M_r of the unknown acid including uncertainty can be written as **155 ± 30.2 g/mol.**

Table 11: Confidence interval for M_r of unknown acid

Mean M_r of unknown acid	Standard deviation of M_r of unknown acid	95% confidence interval for mean M_r of unknown acid
155	12.2	± 30.2

Additionally, a Gran plot can be plotted to determine the end point of the titration. Data *Figure 10* can be found in the *APPENDIX*.

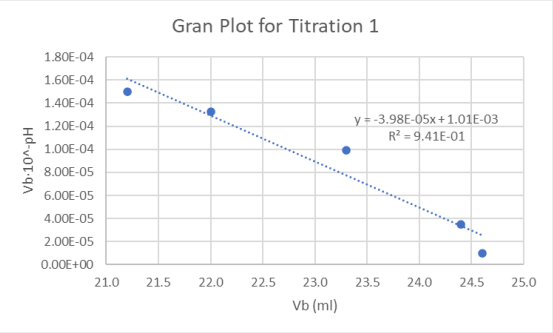

Figure 10: Gran plot for titration 1

The volume of the end point of the titration can be found as the y-intercept of the graph. The equation of the graph is set to equal 0 to find the y-intercept as follows: $0 = -3.98 \cdot 10^{-5}x + 1.01 \cdot 10^{-3}$. This can be evaluated to give a $\boldsymbol{x \approx 25.38 = V_e}$.

ANALYSIS

After analysing the results from the investigation it remained unclear which unknown acid. The unknown acid has a Ka closest to that of nicotinic acid (1.41E-5) and a M_r closest to that of mandelic acid (152.147 g/mol). However, the true identity of the unknown acid analysed in this investigation is potassium bitartrate ($KC_4H_5O_6$). The literature Ka of $KC_4H_5O_6$ is 3.98E-5 and the Ka measured in this investigation was 1.36E-5 ± 1.19E-6. The literature Ka value is significantly outside of the uncertainty range of the calculated value. The possible reasons and errors for this are discussed further in the *EVALUATION*. The literature relative molecular mass of $KC_4H_5O_6$ is 188.177 g/mol and the calculated value was 155 ± 30.2 g/mol. The literature value lies just outside of the calculated value with maximum uncertainty (185.2 g/mol), the reasons for this are explored further in the *EVALUATION*. Additionally, the uncertainty of Ka at 11.4% and the uncertainty of M_r at 5.12% are significantly lower than expected for results which do not match literature values. This indicates that the error is systematic and lies within the method rather than a random error.

Comparing the volume for the end point using the Gran plot method and the derivative method, it can be said that in this case the derivative method is more accurate. The Gran plot method for titration 1 yielded an end point volume of 25.38 ml and the derivative method yielded an end point volume of 24.5 ml. When comparing to the pH curve, visually the derivative method appears to be more accurate. Reasons and errors are evaluated in the *EVALUATION*.

IV. DISCUSSION

EVALUATION

To effectively evaluate this investigation, strengths and weaknesses in the method must be identified, assessed, and improved.

A significant strength within the investigation is the low uncertainty values throughout the measurements which lead to an overall 95% confidence interval of Ka of the unknown acid of 11.4% and the that of the relative molecular mass of the unknown acid of 5.12%. Low uncertainty values indicate precise results and the absence of errors within measurement readings. Whilst this is a positive, in this investigation the results did not match literature values and thus since uncertainties give direct feedback on the method and equipment used. Therefore, it can be determined that there was errors in the method. A prime example of this is the lack of repeat titrations. The reason for this was the lack of available time in the lab to complete this investigation and thus the repeats of the titrations had to be limited. To eliminate this error, gain more accurate results, and to reduce uncertainties, the more repeat titrations should be implemented into the method.

Furthermore, the number of measurements recorded around the equivalence point was not sufficient. After analysing the results it is clear that there were an abundance of measurements before and after equivalence and less near the point of equivalence. This is because near equivalence the pH changes drastically with only a small addition of titrate. Therefore, the pH must be measured more frequently, for example, at every millilitre of titrate added; this was not done in the method of this investigation. In the future, this should be implemented in the method for a better, more accurate pH curve. This would lead to better estimates of equivalence and in turn half-equivalence points which would yield a more precise value for the pKa and Ka of the unknown acid. It should be noted that if this improvement was implemented, then the Gran plot method to estimate the end point volume/point of equivalence would be more accurate than the derivative method and should be used instead. In this investigation there was only 5 data points in the Gran plot causing it to be unreliable.

Another significant flaw in the manner this investigation was carried out was that the volume of NaOH needed for a colour change to occur, i.e. the volume required to neutralise the unknown acid was not properly set at 30 ± 5 ml. From the titration curves, it can be seen that this volume was between 20 and 24 ml. This error is due to the mass of unknown acid in the solution before titration. This mistake in following the method was one of the aspects causing a lower relative molecular mass of the unknown acid. This error can easily be avoided in the future by conducting additional preliminary titrations until the correct mass of unknown acid for a titration with an end point volume of 30 ± 5 ml is observed. The reason this was not done initially was because of the limited lab time.

Additional weaknesses in this investigation could potentially be due to the use of a faulty, uncalibrated pH Probe, or the method of determining when the titration has reached its end point. If there was a faulty probe, pH and changes in pH would not be measured accurately and would lead to the imprecise values of the Ka and relative molecular mass of the unknown acid which were calculated in this investigation. This was the case in this investigation as a colour change was observed at pH 6 and 7 when the phenolphthalein indicator should indicates in pH ranges 8.2-10.0.[2] To avoid this in the future, the pH probe should be calibrated multiple times to ensure it is working properly.

Overall, with the implementation of the suggested improvements, the investigation will lead better results which will better match the Ka and relative molecular mass of $KC_4H_5O_6$.

FURTHER DISCUSSION

This investigation can be advanced and taken further by exploring the real world applications of the identification of unknown acids. For example, when identifying unknown samples of material from the environment. This would be very interesting to see levels of acid pollution in different areas, or how these levels of pollution change over time and attempting to identify a cause for the results. Additionally, in the medical field, it would be interesting to see how the pH of fluids such as blood change due to different medicines or alternatively, an investigation to determine the identity of the compounds within the medicine.

V. REFERENCES

BIBLIOGRAPHY

1. University of California Berkeley; "Acid-Base Reactions: Identification of an Unknown Weak Acid"; *University of California Berkeley*; PDF; Accessed: 04.12.23
2. Imperial College London; "*Acid - Base Indicators and Titrations";* https://www.ch.ic.ac.uk/vchemlib/course/indi/; Accesed 04.12.23
3. Kong, QingKai; Siauw, Timmy; Bayen, Alexandre; "*Python Programming and Numberical Methods*"; https://pythonnumericalmethods.berkeley.edu/notebooks/chapter20.02-Finite-Difference-Approximating-Derivatives.html; Accessed: 04.12.23

APPENDIX

Table 4: Titration 1 data

Raw Data		First derivative		Second Derivative	
V (ml)	pH	V (ml)	dpH/dV	V (ml)	d(dpH/dV)/dV
0.0	4.62	1.0	3.00E-02	1.6	-8.88E-16
2.0	4.65	2.1	1.43E-02	3.4	2.00E-02
2.2	4.68	4.6	1.09E-02	6.1	-2.00E-02
7.0	4.73	7.6	3.95E-03	8.3	8.88E-16
8.2	4.76	9.0	3.35E-03	9.6	-1.00E-02
9.7	4.79	10.3	1.94E-03	10.9	1.00E-02
10.9	4.81	11.5	2.61E-03	12.1	-1.00E-02
12.1	4.84	12.6	1.59E-03	13.0	-1.00E-02
13.1	4.86	13.4	7.49E-04	13.7	1.00E-02
13.6	4.87	14.0	1.43E-03	14.3	8.88E-16
14.3	4.89	14.7	1.37E-03	15.0	-8.88E-16
15.0	4.91	15.3	1.31E-03	15.6	8.88E-16
15.6	4.93	16.0	1.25E-03	16.2	-1.00E-02
16.3	4.95	16.5	6.06E-04	16.8	1.00E-02
16.7	4.96	17.2	1.17E-03	17.6	1.00E-02
17.6	4.98	18.0	1.67E-03	18.3	-1.00E-02
18.3	5.01	18.7	1.07E-03	19.0	1.00E-02
19.0	5.03	19.3	1.55E-03	19.6	8.88E-16
19.6	5.06	20.0	1.50E-03	20.4	3.00E-02
20.3	5.09	20.8	2.89E-03	21.2	1.00E-02
21.2	5.15	21.6	3.24E-03	22.1	8.00E-02
22.0	5.22	22.7	6.62E-03	23.3	3.20E-01
23.3	5.37	23.9	1.97E-02	24.2	9.00E-02
24.4	5.84	24.5	2.29E-02	24.6	-1.80E-01
24.6	6.4	24.7	1.54E-02	24.8	-1.00E-01
24.8	6.78	24.8	1.13E-02	24.9	-1.70E-01
24.8	7.06	24.9	4.42E-03	25.0	-5.00E-02
25.0	7.17	25.1	2.40E-03	25.1	-2.00E-02
25.1	7.23	25.2	1.59E-03	25.2	8.88E-16
25.2	7.27	25.3	1.58E-03	25.4	2.00E-02
25.4	7.31	25.6	2.35E-03	25.7	-4.00E-02
25.7	7.37	25.8	7.75E-04	25.9	-2.00E-02
25.9	7.39	26.0	0.00E+00	26.0	2.00E-02
26.0	7.39	26.1	7.66E-04	26.2	1.00E-02
26.2	7.41	26.3	1.14E-03	26.7	5.00E-02
26.4	7.44	27.0	2.96E-03	27.6	-1.00E-02
27.6	7.52	28.2	2.48E-03	28.9	-2.00E-02
28.8	7.59	29.7	1.69E-03	30.6	8.88E-16
30.5	7.64	31.6	1.58E-03	32.6	-2.00E-02
32.7	7.69	33.6	8.93E-04	34.5	-1.00E-02
34.5	7.72	35.4	5.66E-04	36.3	-8.88E-16
36.2	7.74	37.2	5.38E-04		-8.88E-16
38.2	7.76				

Table 5: Titration 2 data

Raw Data		First derivative		Second Derivative	
V (ml)	pH	V (ml)	dpH/dV	V (ml)	d(dpH/dV)/dV
0.0	4.65	0.5	0.00E+00	1.1	3.00E-02
1.0	4.65	1.6	3.00E-02	2.2	-1.00E-02
2.2	4.68	2.7	2.00E-02	3.2	-8.88E-16
3.2	4.7	3.8	2.00E-02	4.4	1.00E-02
4.3	4.72	5.0	3.00E-02	5.5	-1.00E-02
5.6	4.75	6.1	2.00E-02	6.5	8.88E-16
6.5	4.77	6.9	2.00E-02	7.3	-8.88E-16
7.3	4.79	7.8	2.00E-02	8.2	-1.00E-02
8.2	4.81	8.7	1.00E-02	9.1	3.00E-02
9.1	4.82	9.6	4.00E-02	9.9	-2.00E-02
10.0	4.86	10.3	2.00E-02	10.7	-1.00E-02
10.6	4.88	11.1	1.00E-02	11.5	2.00E-02
11.5	4.89	12.0	3.00E-02	12.5	1.00E-02
12.4	4.92	13.0	4.00E-02	13.5	-1.00E-02
13.5	4.96	14.0	3.00E-02	14.3	-2.00E-02
14.4	4.99	14.6	1.00E-02	14.8	2.00E-02
14.7	5	15.1	3.00E-02	15.5	1.00E-02
15.5	5.03	15.9	4.00E-02	16.2	-2.00E-02
16.3	5.07	16.5	2.00E-02	16.7	8.88E-16
16.7	5.09	16.9	2.00E-02	17.2	3.00E-02
17.1	5.11	17.4	5.00E-02	17.8	3.00E-02
17.7	5.16	18.1	8.00E-02	18.5	-2.00E-02
18.5	5.24	18.9	6.00E-02	19.2	9.00E-02
19.2	5.3	19.5	1.50E-01	19.7	-9.00E-02
19.8	5.45	20.0	6.00E-02	20.1	9.00E-02
20.1	5.51	20.3	1.50E-01	20.4	8.00E-02
20.4	5.66	20.5	2.30E-01	20.7	2.40E-01
20.6	5.89	20.8	4.70E-01	21.0	-1.10E-01
21.0	6.36	21.1	3.60E-01	21.2	-4.00E-02
21.2	6.72	21.4	3.20E-01	21.5	-6.00E-02
21.5	7.04	21.6	2.60E-01	21.7	-2.00E-01
21.7	7.3	21.9	6.00E-02	22.0	-8.88E-16
22.0	7.36	22.1	6.00E-02	22.2	-3.00E-02
22.2	7.42	22.4	3.00E-02	22.5	-1.00E-02
22.5	7.45	22.6	2.00E-02	22.8	1.00E-02
22.7	7.47	22.9	3.00E-02	23.3	5.00E-02
23.1	7.5	23.7	8.00E-02	24.3	-4.00E-02
24.3	7.58	24.9	4.00E-02	25.4	-1.00E-02
25.4	7.62	25.9	3.00E-02	26.6	2.00E-02
26.4	7.65	27.3	5.00E-02	28.2	-2.00E-02
28.2	7.7	29.1	3.00E-02	30.3	1.00E-02
30.0	7.73	31.4	4.00E-02	32.9	-1.00E-02
32.8	7.77	34.4	3.00E-02	36.4	0.00E+00
36.0	7.8	38.3	3.00E-02		
40.6	7.83				

Table 6: Titration 3 data

Raw Data		First derivative		Second Derivative	
V (ml)	pH	V (ml)	dpH/dV	V (ml)	d(dpH/dV)/dV
0.0	4.63	1.2	4.00E-02	1.8	1.00E-02
2.4	4.67	2.5	5.00E-02	3.4	-2.00E-02
2.5	4.72	4.3	3.00E-02	5.6	1.00E-02
6.0	4.75	6.9	4.00E-02	7.7	-2.00E-02
7.8	4.79	8.5	2.00E-02	9.1	1.00E-02
9.2	4.81	9.7	3.00E-02	10.3	0.00E+00
10.2	4.84	10.9	3.00E-02	11.6	1.00E-02
11.5	4.87	12.3	4.00E-02	13.0	0.00E+00
13.0	4.91	13.8	4.00E-02	14.5	-1.00E-02
14.6	4.95	15.1	3.00E-02	15.6	2.00E-02
15.6	4.98	16.2	5.00E-02	16.6	-1.00E-02
16.7	5.03	17.1	4.00E-02	17.4	-2.00E-02
17.5	5.07	17.8	2.00E-02	18.1	2.00E-02
18.0	5.09	18.4	4.00E-02	18.7	1.00E-02
18.7	5.13	19.0	5.00E-02	19.3	8.88E-16
19.3	5.18	19.6	5.00E-02	19.9	4.00E-02
19.9	5.23	20.3	9.00E-02	20.5	-3.00E-02
20.6	5.32	20.8	6.00E-02	21.0	5.00E-02
21.0	5.38	21.3	1.10E-01	21.5	3.10E-01
21.5	5.49	21.8	4.20E-01	22.1	1.60E-01
22.1	5.91	22.4	5.80E-01	22.6	6.00E-02
22.6	6.49	22.8	6.40E-01	23.1	-3.80E-01
23.0	7.13	23.3	2.60E-01	23.6	-1.80E-01
23.6	7.39	23.9	8.00E-02	24.2	-4.00E-02
24.2	7.47	24.5	4.00E-02	24.8	1.00E-02
24.8	7.51	25.2	5.00E-02	25.7	1.00E-02
25.5	7.56	26.3	6.00E-02	27.1	-1.00E-02
27.0	7.62	28.0	5.00E-02	28.9	-2.00E-02
28.9	7.67	29.8	3.00E-02	30.9	1.00E-02
30.6	7.7	32.0	4.00E-02	33.3	1.00E-02
33.4	7.74	34.7	5.00E-02	35.8	-5.00E-02
35.9	7.79	36.9	0.00E+00	37.9	2.00E-02
37.9	7.79	39.0	2.00E-02		1.00E-02
40.0	7.81				

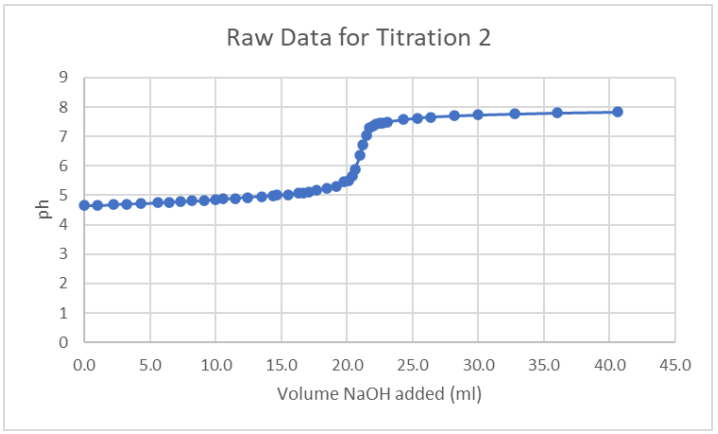

Figure 4: Raw data for titration 1 (pH curve)

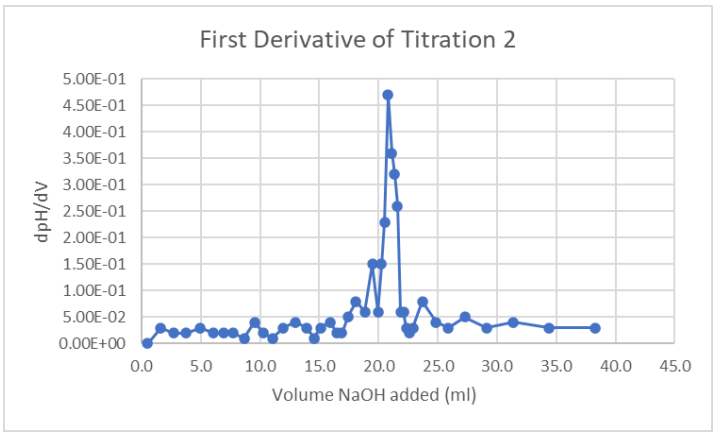

Figure 5: First derivative of titration 2

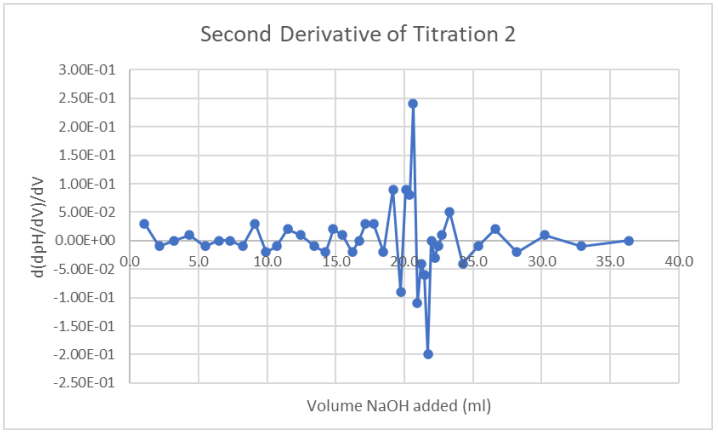

Figure 6: Second derivative of titration 2

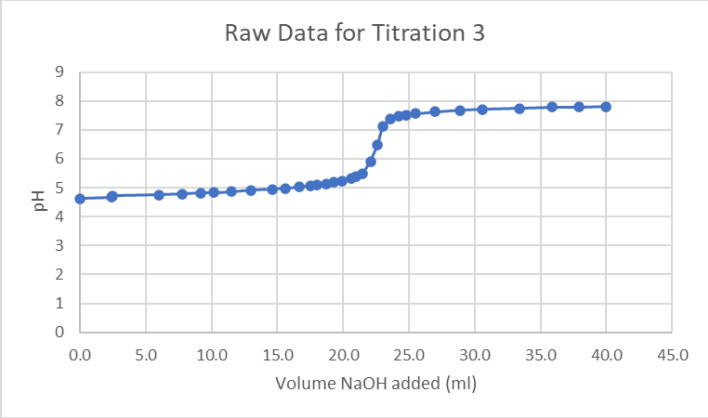

Figure 7: Raw data for titration 1 (pH curve)

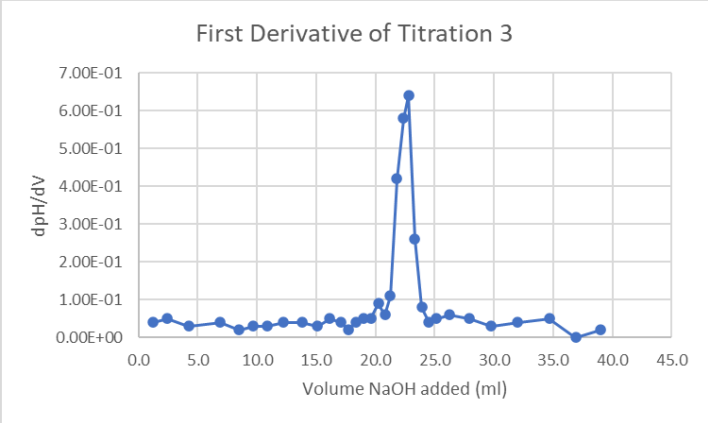

Figure 8: First derivative of titration 3

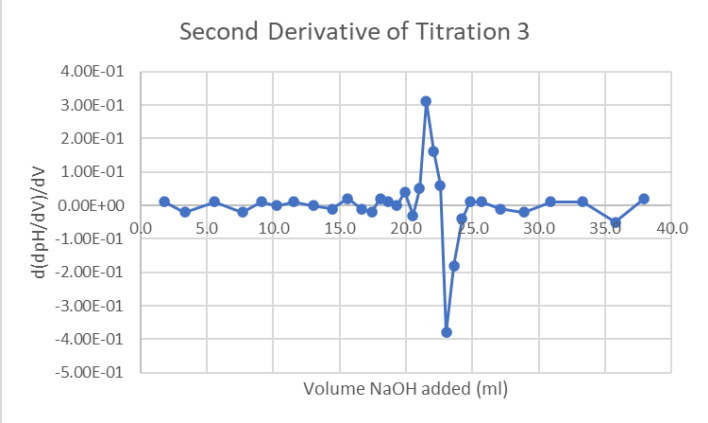

Figure 9: Second derivative of titration 3

Table 12: Gran plot data

Volume of NaOH added (ml)	pH of unknown acid	$Vb \cdot 10^{-pH}$
21.2	5.15	1.50E-04
22.0	5.22	1.33E-04
23.3	5.37	9.94E-05
24.4	5.84	3.53E-05
24.6	6.4	9.79E-06