A 100.-mL Sample Of A 0.10 M Solution Of H3PO4 Is Titrated With 0.20 M NaOH. What Volume Of Base Must

A 100.-mL Sample Of A 0.10 M Solution Of H3PO4 Is Titrated With 0.20 M NaOH. What Volume Of Base Must be added to completely neutralize the acid? Understanding how to perform this titration involves grasping the concepts of molarity, molar ratios, and stoichiometry. This article will walk you through the step-by-step process of calculating the volume of NaOH required to neutralize a given volume of phosphoric acid (H_3PO_4) solution, providing a comprehensive explanation suitable for students and professionals alike.

Understanding the Basics of Acid-Base Titration

What Is Titration?

Titration is a laboratory procedure used to determine the concentration of an unknown solution by adding a volume of a standard solution of known concentration until the reaction reaches its endpoint. The point at which the reaction is complete is often indicated by a color change using an indicator or by reaching a specific pH.

Significance of Molarity and Volume

- Molarity (M) indicates how many moles of solute are present in one liter of solution.
- The volume of solutions used during titration, measured in milliliters (mL), helps determine the amount of reactant needed for complete neutralization.

Understanding the Reaction Between H_3PO_4 and NaOH

Balanced Chemical Equation

Phosphoric acid (H_3PO_4) is a triprotic acid, meaning it can donate three protons (H^+), and reacts with sodium hydroxide (NaOH) in a 1:1 molar ratio for each proton:

\[\mathrm{H_3PO_4 + 3NaOH \rightarrow Na_3PO_4 + 3H_2O} \]

However, to be precise, the titration involves stepwise neutralization:

- First proton: $H_3PO_4 + NaOH \rightarrow NaH_2PO_4$
- Second proton: $NaH_2PO_4 + NaOH \rightarrow Na_2HPO_4$
- Third proton: $Na_2HPO_4 + NaOH \rightarrow Na_3PO_4$

The overall reaction reflects three molar equivalents of NaOH reacting with one mole of H_3PO_4.

Molar Ratios

- 1 mol of H_3PO_4 reacts with 3 mol of NaOH.
- Therefore, the stoichiometric ratio is 1:3.

Calculating the Moles of H_3PO_4 in the Sample

Given Data

- Volume of H_3PO_4 solution: 100 mL (0.100 L)
- Concentration of H_3PO_4: 0.10 M

Calculating Moles of H_3PO_4

$$
\text{Moles of } H_3PO_4 = \text{Concentration} \times \text{Volume} = 0.10\, \text{mol/L} \times 0.100\, \text{L} = 0.010\, \text{mol}
$$

This means there are 0.010 moles of phosphoric acid in the sample.

Determining the Moles of NaOH Required

Using Stoichiometry

Since three moles of NaOH are required per mole of H_3PO_4:

$$
\text{Moles of NaOH needed} = 3 \times 0.010\, \text{mol} = 0.030\, \text{mol}
$$

Thus, 0.030 moles of NaOH are needed to fully neutralize the acid.

Calculating the Volume of NaOH Needed

Given Data

- Concentration of NaOH: 0.20 M

Using Moles and Molarity to Find Volume

$$
\text{Volume of NaOH} = \frac{\text{Moles of NaOH}}{\text{Concentration of NaOH}}
= \frac{0.030\, \text{mol}}{0.20\, \text{mol/L}} = 0.15\, \text{L}
$$

Converting to milliliters:

$$
0.15\, \text{L} \times 1000\, \text{mL/L} = 150\, \text{mL}
$$

Therefore, 150 mL of 0.20 M NaOH is required to completely neutralize the 100 mL of 0.10 M H_3PO_4 solution.

Summary of Key Steps

1. Calculate the moles of H_3PO_4 in the sample: 0.010 mol.

2. Determine the molar ratio between H_3PO_4 and NaOH: 1:3.

3. Calculate the moles of NaOH needed: 0.030 mol.

4. Use the molarity of NaOH to find the volume required: 150 mL.

Additional Considerations in Titration

Choosing the Right Indicator

- For strong acid-strong base titrations, phenolphthalein is commonly used because it changes color around pH 8.3 to 10.
- For phosphoric acid, which is a weak triprotic acid, the endpoint depends on the degree of neutralization and the indicator's pH range.

Understanding Equivalence Point

- The equivalence point is reached when the amount of NaOH added equals the amount needed to neutralize all acidic protons.
- In triprotic acids like H_3PO_4, the titration curve can show multiple equivalence points, but the primary focus is on the complete neutralization of all three protons.

Practical Tips for Accurate Titration

- Use a clean burette to avoid contamination.
- Add NaOH slowly near the endpoint.
- Record the volume precisely when the indicator signals the endpoint.
- Repeat titrations to ensure accuracy and consistency.

Conclusion

Performing a titration requires understanding the stoichiometry of the reaction, calculating the number of moles involved, and translating that into the volume of titrant needed. In the case of titrating a 100-mL sample of 0.10 M H_3PO_4 with 0.20 M NaOH, approximately 150 mL of NaOH is necessary to achieve complete neutralization. Mastery of these calculations not only helps in laboratory settings but also deepens the understanding of acid-base chemistry fundamentals.

By following these steps and understanding the underlying principles, students and chemists can confidently perform titrations, analyze data, and interpret results accurately.

Frequently Asked Questions

How do you determine the volume of NaOH needed to titrate a 100 mL sample of 0.10 M H3PO4?

Use the molarity and volume of H3PO4 to find moles, then use NaOH's molarity to calculate the required volume: moles H3PO4 = 0.10 M × 0.100 L = 0.010 mol; since H3PO4 is triprotic, total moles of NaOH needed = 3 × 0.010 mol = 0.030 mol; volume of NaOH = 0.030 mol / 0.20 M = 0.15 L or 150 mL.

Why is the molarity of NaOH important in calculating the titration volume?

The molarity of NaOH indicates how many moles of NaOH are present per liter, allowing you to determine the volume needed to provide the exact number of moles required to neutralize the acid based on stoichiometry.

What is the significance of the triprotic nature of H3PO4 in this titration problem?

H3PO4 can donate three protons per molecule, so the total moles of NaOH required are three times the moles of H3PO4 initially present, affecting the volume calculation for complete neutralization.

How do you account for the multiple equivalents in the titration of H3PO4 with NaOH?

Since each H3PO4 molecule releases three protons, the equivalents of acid are tripled, meaning three moles of NaOH are needed per mole of H3PO4 for complete neutralization.

What is the purpose of performing a titration with NaOH on a phosphoric acid solution?

Titration helps determine the concentration or purity of the acid, or to find the amount of base needed to neutralize a known volume of acid in analytical chemistry.

If the initial volume of H3PO4 is increased, how does that affect the volume of NaOH needed?

The volume of NaOH required increases proportionally with the initial volume of H3PO4, assuming concentration stays the same, because more acid requires more base for neutralization.

What are the units used in calculating titration volumes, and why are they important?

Volumes are typically expressed in liters (L) or milliliters (mL). Consistent units are crucial for accurate calculations, especially when converting between molarity, moles, and volume.

How would the calculation change if a different concentration of NaOH was used?

You would adjust the volume calculation by dividing the total moles of NaOH needed by the new NaOH molarity. For example, if NaOH concentration increases, the required volume decreases proportionally.

Additional Resources

Titration of a 0.10 M H_3PO_4 Solution with 0.20 M NaOH: A Comprehensive Analysis

Titration processes are fundamental in analytical chemistry, providing precise quantitative information about the concentration of unknown solutions. In this context, titrating a 100 mL sample of a 0.10 M solution of phosphoric acid (H_3PO_4) with a 0.20 M sodium hydroxide (NaOH) solution exemplifies classic acid-base titration principles. This process not only demonstrates the stoichiometry involved in polyprotic acid-base reactions but also reinforces essential concepts such as molarity calculations, equivalence points, and titration curves. This comprehensive review aims to dissect every aspect of such a titration, from theoretical foundations to practical applications, ensuring a clear understanding of the underlying chemistry and methodology.

Understanding the Chemistry: H_3PO_4 and NaOH Reaction Dynamics

The Nature of Phosphoric Acid (H_3PO_4)

Phosphoric acid is a triprotic acid, meaning it can donate three protons (H^+) per molecule during dissociation:

$$ \mathrm{H_3PO_4} \rightarrow \mathrm{H^+} + \mathrm{H_2PO_4^-} $$

$$ \mathrm{H_2PO_4^-} \rightarrow \mathrm{H^+} + \mathrm{HPO_4^{2-}} $$

$$ \mathrm{HPO_4^{2-}} \rightarrow \mathrm{H^+} + \mathrm{PO_4^{3-}} $$

Each dissociation step has a distinct acid dissociation constant (Ka), with the first being the strongest:

- $pK_{a1} \approx 2.15$
- $pK_{a2} \approx 7.20$
- $pK_{a3} \approx 12.35$

This stepwise dissociation influences the titration curve, resulting in multiple equivalence points corresponding to each proton's removal.

The Role of Sodium Hydroxide (NaOH)

NaOH is a strong base that completely dissociates in aqueous solution:

$$ \mathrm{NaOH} \rightarrow \mathrm{Na}^+ + \mathrm{OH}^- $$

It reacts with each proton released by H_3PO_4 in a neutralization process:

$$ \mathrm{H_3PO_4} + \mathrm{OH}^- \rightarrow \mathrm{H_2PO_4^-} + \mathrm{H_2O} $$

and subsequently with the ions formed:

$$ \mathrm{H_2PO_4^-} + \mathrm{OH}^- \rightarrow \mathrm{HPO_4^{2-}} + \mathrm{H_2O} $$

$$ \mathrm{HPO_4^{2-}} + \mathrm{OH}^- \rightarrow \mathrm{PO_4^{3-}} + \mathrm{H_2O} $$

Understanding these reactions is crucial because they determine the volume of NaOH needed to reach various equivalence points during titration.

Calculating the Volume of NaOH Required

Initial Data and Assumptions

- Volume of H_3PO_4 solution: 100 mL (0.100 L)
- Concentration of H_3PO_4: 0.10 M
- Concentration of NaOH: 0.20 M

The goal is to find out how much NaOH is needed to fully neutralize the acid, considering the stepwise dissociation, or to reach a specific equivalence point.

Number of Moles of H_3PO_4 in the Sample

Calculating the moles of phosphoric acid:

$$ \text{Moles of } H_3PO_4 = \text{Molarity} \times \text{Volume} $$

$$ = 0.10\, \mathrm{mol/L} \times 0.100\, \mathrm{L} = 0.010\, \mathrm{mol} $$

Since phosphoric acid is triprotic, the total number of protons available for titration is:

$$ 0.010\, \mathrm{mol} \times 3 = 0.030\, \mathrm{mol} $$

Stoichiometry of Neutralization

The titration involves sequential reactions, but for the purpose of calculating the total volume needed to fully neutralize all three protons, the overall reaction can be simplified as:

$$ \mathrm{H_3PO_4} + 3\, \mathrm{OH}^- \rightarrow \mathrm{PO_4^{3-}} + 3\, \mathrm{H_2O} $$

This indicates that 1 mol of H_3PO_4 requires 3 mol of NaOH for complete neutralization:

$$ \text{NaOH needed} = 3 \times 0.010\, \mathrm{mol} = 0.030\, \mathrm{mol} $$

Calculating the Volume of NaOH Needed

Using the molarity of NaOH:

$$ \text{Volume} = \frac{\text{Moles of NaOH}}{\text{Concentration of NaOH}} $$

$$ = \frac{0.030\, \mathrm{mol}}{0.20\, \mathrm{mol/L}} = 0.15\, \mathrm{L} = 150\, \mathrm{mL} $$

Therefore, approximately 150 mL of 0.20 M NaOH is required to completely titrate the 100 mL sample of 0.10 M H_3PO_4 to the third equivalence point.

Understanding the Titration Curve and Equivalence Points

Features of the Titration Curve

A titration curve for phosphoric acid with sodium hydroxide displays multiple inflection points, each corresponding to the neutralization of a proton:
- First equivalence point (~pH 4.7): Neutralization of the first proton, resulting in $H_2PO_4^-$.
- Second equivalence point (~pH 7.2): Neutralization of the second proton, forming HPO_4^{2-}.
- Third equivalence point (~pH 12.3): Complete neutralization to PO_4^{3-}.

Understanding these points helps in designing titrations for specific analytical purposes, such as determining the concentration of phosphoric acid or its dissociation constants.

Practical Significance of Multiple Equivalence Points

- Provides insights into the polyprotic nature of phosphoric acid.
- Allows for stepwise analysis, useful in complex titrations.
- Helps in calibration and validation of titration methods.

Pros and Cons of Titration Methodology in This Context

Pros:
- Accuracy and Precision: When performed carefully, titrations yield highly accurate concentration data.
- Simplicity: The method relies on straightforward stoichiometric calculations.
- Versatility: Applicable for various acids, bases, and complex mixtures.
- Visual Endpoint Detection: Color indicators (like phenolphthalein or methyl orange) facilitate endpoint identification.

Cons:
- Polyprotic Complexity: Multiple equivalence points can complicate interpretation.
- Indicator Limitations: Choice of indicator affects endpoint accuracy, especially near multiple equivalence points.
- Time-Consuming: Sequential titrations or slow addition can prolong analysis.
- Potential for Error: Misreading titrant volume, incomplete reactions, or side reactions can lead to inaccuracies.

Practical Applications and Considerations

Analytical Uses

- Determining phosphoric acid concentrations in industrial samples.
- Monitoring purity in manufacturing processes.
- Studying acid dissociation constants experimentally.

Experimental Tips

- Use appropriate indicators matching the pH range of the equivalence points.
- Perform titrations slowly near the equivalence points for accuracy.
- Conduct multiple titrations to ensure reproducibility.
- Record the volume precisely to minimize errors.

Advanced Techniques

- Potentiometric titration using pH electrodes for more precise endpoint detection.
- Spectrophotometric analysis in complex matrices.

Conclusion

The titration of a 100 mL sample of 0.10 M H_3PO_4 with 0.20 M NaOH exemplifies key principles of acid-base chemistry, stoichiometry, and analytical methodology. Calculations reveal that approximately 150 mL of NaOH is necessary to fully neutralize the phosphoric acid to its third equivalence point. Understanding the stepwise dissociation of H_3PO_4 and the corresponding titration curve is crucial for accurate analysis and interpretation. While titration remains a cornerstone technique due to its accuracy and versatility, awareness of its limitations—especially with polyprotic acids—is essential for precise and reliable results. By integrating theoretical knowledge with practical considerations, chemists can effectively utilize titration methods for a wide range of analytical applications, ensuring robust and meaningful data collection.

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