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Investigating Chemiluminescence for Enhanced Forensics and Water Safety

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Abstract

Chemiluminescence is the phenomenon of emitting light as a result of a chemical reaction without external light sources. This research explores the principles of chemiluminescence, real-life applications, luminol's function in forensic science, and the effect of temperature on chemiluminescent glow intensity. The project further proposes a portable device "Aqualume" utilizing chemiluminescence and Arduino based light detection system to detect water contaminants.

Keywords: Chemiluminescence, Luminol, Forensic Science, Temperature, Water Contamination

1. Introduction

- Chemiluminescence is a fascinating phenomenon where light is produced as a result of a chemical reaction. This process does not require external light sources but instead relies on the energy released during a chemical reaction to produce visible light. The light emitted during chemiluminescence is often referred to as "cold light" because it occurs without significant heat production, unlike incandescent light sources.
- One of the most well-known examples of chemiluminescence in everyday life is the glow stick. When the stick is bent, it breaks an inner glass vial containing hydrogen peroxide, which then mixes with a solution of diphenyl oxalate and a fluorescent dye. The chemical reaction between these substances produces light, demonstrating the principles of chemiluminescence in a simple and accessible way.

2. Real Life Application

- **Forensic Science:** Chemiluminescence is widely used in forensic science for the detection of blood, even if it's washed away.
- **Medical Diagnostics:** Chemiluminescent assays are employed to detect specific biomolecules. For example, it is used in techniques like ELISA and Western blotting to detect proteins at very low concentrations, providing high sensitivity and specificity.
- **Environmental Monitoring:** It is used to monitor pollutants in the environment. For instance, it can detect nitrogen oxides (NOx) in the air, which are important indicators of air quality and pollution levels. This method offers high sensitivity and can detect pollutants at very low concentrations.
- **Industrial Applications**: In industrial settings, chemiluminescent sensors are used for gas analysis and combustion monitoring. These sensors can detect specific chemicals and radicals in combustion processes, helping to optimize industrial operations and ensure safety.
- **Biological Research:** Bioluminescence, a type of chemi luminescence found in living organisms, is used in biological research to study cellular processes. Fireflies and certain marine organisms produce

light through bioluminescent reactions, which are harnessed in laboratory settings to investigate gene expression, cell signaling, and other biological phenomena

3. Working of Chemiluminescence

In chemiluminescence, when a chemical reaction occurs, it releases energy that excites the electrons in one of the reacting molecules from their ground state (lowest energy) to an excited state. This excitation causes the electrons to jump to a higher energy level and also form an excited state intermediate. When these excited electrons return back to their ground state, they release the excess energy in the form of photons, which produce the visible light.

Step-by-step breakdown of the process:

1. **Reactant Mixing**: Two or more reactants come together to form an intermediate compound.
2. *Consider 2 reactants A and B and they combine to form product C:* $A + B \rightarrow C$.
3. **Formation of Excited State**: The energy released during the chemical reaction promotes electrons in the intermediate to a higher energy level, creating an excited state.
4. *The product C converts to further product, which is produced in an electronically excited state:* $C \rightarrow D^*$
5. **Emission of Light**: As the excited state intermediate returns to its ground state, it releases the excess energy in the form of photons (light).

D then emits a photon (hv), to give the ground state of D:* $D^* \rightarrow D + hv$

Factors affecting the rate of chemiluminescent reactions:

Different rates occur for different chemical reactions. Temperature, concentration, use of a catalyst, and particle size are four factors that primarily affect the rate of a chemical reaction.

- **Role of Catalysts and Enhancers**: Catalysts can significantly increase the efficiency of chemiluminescent reactions. In biological systems, enzymes like luciferase catalyze the oxidation of luciferin, producing light. In synthetic systems, enhancers like certain dyes can shift the wavelength of the emitted light to the desired range.
- **Temperature and pH Effects**: The rate and intensity of chemiluminescent reactions can be affected by temperature and pH. Higher temperatures generally increase the reaction rate but may decrease the duration of light emission. The pH can also influence the efficiency and color of the emitted light, with certain reactions requiring specific pH conditions for optimal performance.

4. Working of Luminol in Crime Scene

Luminol is a chemical compound with the unique ability to emit light through a process called chemiluminescence. This property is particularly useful in forensic science and its working in crime scene investigations involves the following steps:

4.1. Preparation of the Luminol Solution:

A solution of luminol is prepared, typically containing sodium hydroxide (NaOH) and hydrogen peroxide (H_2O_2). Sodium hydroxide provides the hydroxide ions (OH^-) necessary for the initial step of the reaction, while hydrogen peroxide acts as an oxidizing agent.

4.2. Activation of Luminol:

When luminol comes into contact with hydroxide ions, it forms a dianion, (a molecule with two negative charges). This dianion is crucial for the subsequent reactions that lead to luminescence.

4.3.Catalysis by Iron in Blood:
The critical step in the chemiluminescence process is the oxidation of luminol. Hydrogen peroxide decomposes to produce oxygen, but this reaction is slow. The presence of a catalyst, such as the iron in hemoglobin (an iron-containing protein in red blood cells), accelerates the production of oxygen from hydrogen peroxide. The iron in the blood acts as this catalyst, significantly speeding up the reaction.
$2\ H_2O_2 \rightarrow 2\ H_2O + O_2$
4.4.Formation of Excited State and Light Emission:
The oxygen produced reacts with the luminol dianion to form an excited state intermediate. This intermediate is unstable and quickly decomposes to form 5-aminophthalic acid, releasing energy in the form of photons. The electrons in the intermediate drop from an excited state to their ground state, emitting blue light in the process.
4.5.Detection and Documentation:
To detect blood, crime scene investigators spray the luminol solution over the area under investigation. In the presence of blood, the reaction produces a blue glow, which lasts for about 30 seconds. This luminescence can be observed in a dark room and documented using long-exposure photography or videotape.
The use of luminol allows investigators to detect even trace amounts of blood, as only a small amount of iron is required to catalyze the reaction. This makes luminol an invaluable tool in forensic science for uncovering evidence that might not be visible to the naked eye.

5. Experiment: Investigating how temperature variation affects the glow produced
5.1 Materials Required
- Luminol Mixture (Luminol + Sodium Carbonate)
- Activator (Sodium Perborate Tetrahydrate)
- Catalyst (Copper Sulphate Pentahydrate)
- Scoop
- Graduated cup
- Water of different temperatures (0°C, 25°C, 100°C)

5.2 Procedure
- **Step 1:** Collect water at 3 different temperatures. First, keep a cup of water at roughly 100°C by boiling it. Then, keep a cup of water at roughly 0°C by freezing it. Finally, keep some water at room temperature. (Here, I have assumed mine as 25°C)
- **Step 2:** Take a cup and add 2 scoops of Luminol and Sodium Carbonate Mixture.
- **Step 3:** Then add 1 scoop of Sodium Perborate Tetrahydrate. This acts as an oxidizing chemical and can be taken as a substitute for Hydrogen Peroxide.
- **Step 4:** Then add 1 scoop of Copper Sulphate Pentahydrate. This can substitute the role of blood as a catalyst.
- **Step 5:** Mix the cup well and make the room dark for best results.
- **Step 6:** Add the hot water (100°C).
- **Step 7:** Observe the brightness of the glow and rate it from a scale of 1 – 10. Note it down.
- **Step 8:** Repeat steps 2 – 7 with normal water (25°C) and cold water (0°C). Compare the brightness in the 3 cases and draw conclusions.

5.3 Observation

100 C (Hot water)	25 C (Normal Water)	0C (Cold water)
		

Figure 1: Observation1 (taken by Jeslyn)

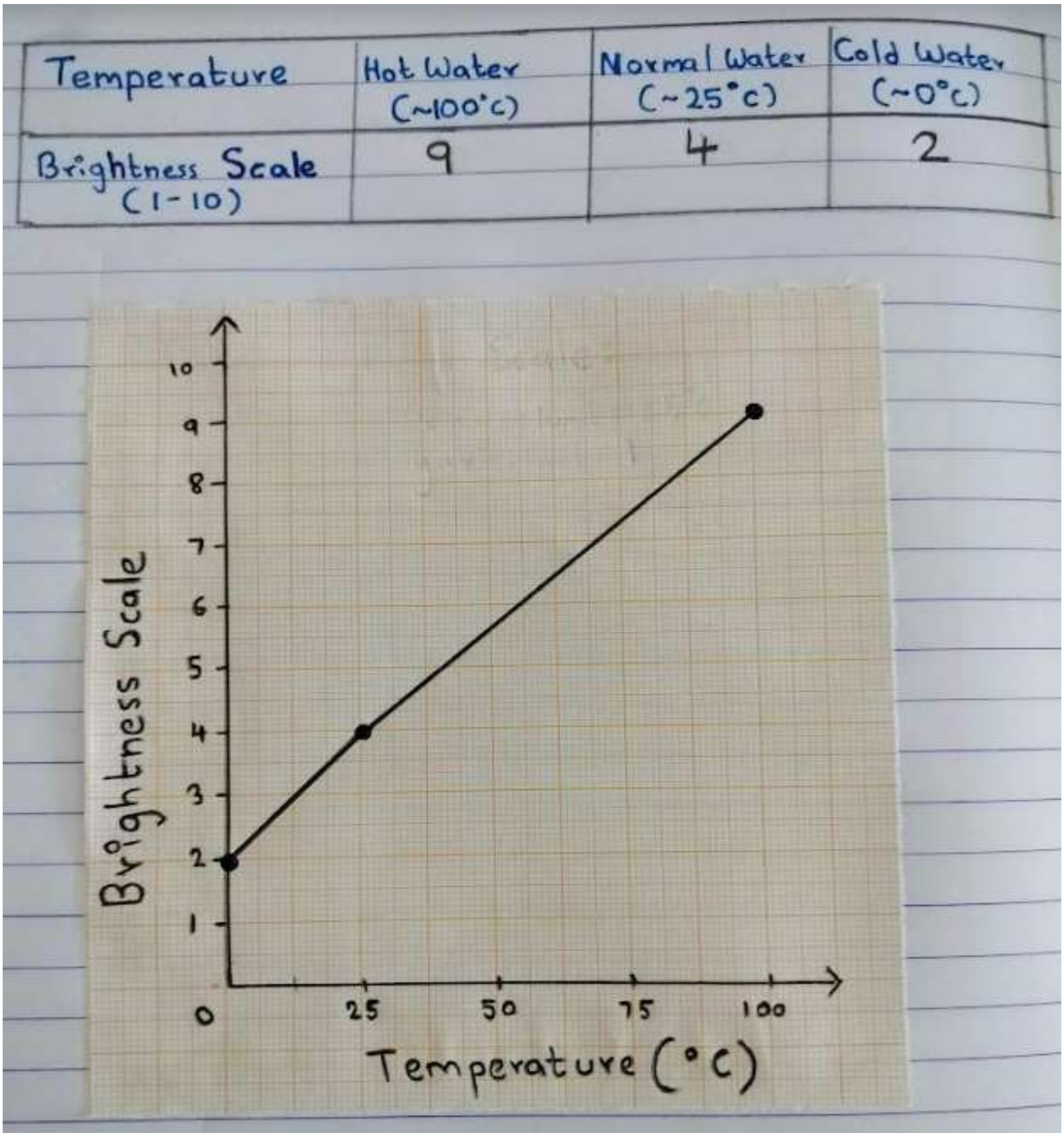

Figure 2: Observation 2 (taken by Jeslyn)

6. Evidence

Figure 3: Evidence photos (taken by Jeslyn)

7. Conclusion of Experiment

From the table and graph obtained, we can see that the glow was highest for warm water and lowest for cold water. This proves that temperature does affect the glow of the solution. Higher temperature had a higher reaction time and produced higher brightness due to more frequent collisions with a higher kinetic energy. Therefore, investigators ought to use luminol in warmer temperatures for a brighter glow.

8. Extension Project: Aqualume

I have extended my research project on chemiluminescence to make a project using technology-driven solutions to address global grand challenges.

Chemiluminescence is the emission of light as the result of a chemical reaction, i.e. a chemical reaction that results in a flash or glow of light.

- **Project:** Aqualume
- **Global Grand Challenge :** Water
- **Menacing Problem:** Water contamination is a significant global issue, especially in poor and underdeveloped regions. Simple, cost-effective, and traditional water purification methods have

existed since immemorial. Methods of detecting pollutants already exist but they are time-consuming, costly, and require sophisticated equipment.

- **My solution** is to develop a simple portable chemiluminescence-based water contamination detection device.
- **Concept Overview**: The device uses chemiluminescence reactions to detect specific contaminants in water, providing real-time results. The core principle is that certain chemicals, when reacting with the contaminants, emit light. Then my Arduino system will detect the light/ glow emitted through the LDR (Light Dependent Resistor) and alert the user through the LCD.
- **Chemistry:** Luminol (with perborate) detects metal contaminants/ pesticides in water
- **Further extensions:** (In the future, the project can be extended to include the following chemicals in layers to detect the corresponding contaminants)
- Dioxetane Derivatives => Heavy Metals, Luciferase (ATP) Detection Kits => Pathogens (e.g., Bacteria), Luminol with Enhancers => Organic Pollutants (e.g., Polycyclic Aromatic Hydrocarbons)
- **Prototype**:
  Part 1 - cup with luminol mixture, upon adding (contaminated) water, produces a glow.
  Part 2 - Arduino setup that uses LDR to detect that glow and displays danger through LCD.

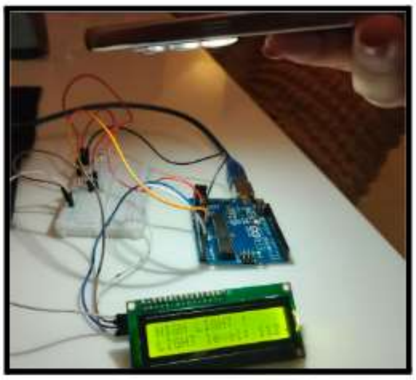

Figure 4: Prototyping (taken by Jeslyn)

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