General- Physics-2 Q4 Week-8

Physical Education (Negros Occidental National Science High School)

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DEPARTMENT OF EDUCATION
SCHOOLS DIVISION OF NEGROS ORIENTAL
REGION VII
Kagawasan Ave., Daro, Dumaguete City, Negros Oriental

THE PHOTOELECTRIC EFFECT AND RADIOACTIVITY

for GENERAL PHYSICS 2/ Grade 12/ Quarter 4/ Week 8

SELF-LEARNING KIT

NegOr_Q4_GenPhysics2_SLKWeek8_v2

FOREWORD

This Self-Learning Kit is designed to cater your needs as STEM students for Modular Distance Learning. It is carefully planned to holistically develop your life-long learning skills. This serves as a guide for you to understand the concepts on photoelectric effect and radioactivity.

This kit enables you to explain the photoelectric effect using the idea of light quanta or photons. How light travels through space is also explained. In addition, the role of energy in the process of atomic emission and absorption is given emphasis. This focuses on how emission of a photon occurred and what happened to an atom upon absorbing this photon. Lastly, sample calculations of radioisotope activity using the concept of half-life are also presented in this kit. This will allow you to enhance your mathematical skills in dealing with problems. One application of radioactivity such as smoke detector is also tackled in order for you to appreciate the importance of the lesson to everyday life.

OBJECTIVES

At the end of this Self-Learning Kit, you should be able to:
K: explain the photoelectric effect;
: explain qualitatively the properties of atomic emission and absorption spectra;
S: calculate radioisotope activity using the concept of half-life; and
A: recognize the importance of radioactivity such as but not limited to the use of smoke detector.

LEARNING COMPETENCIES:

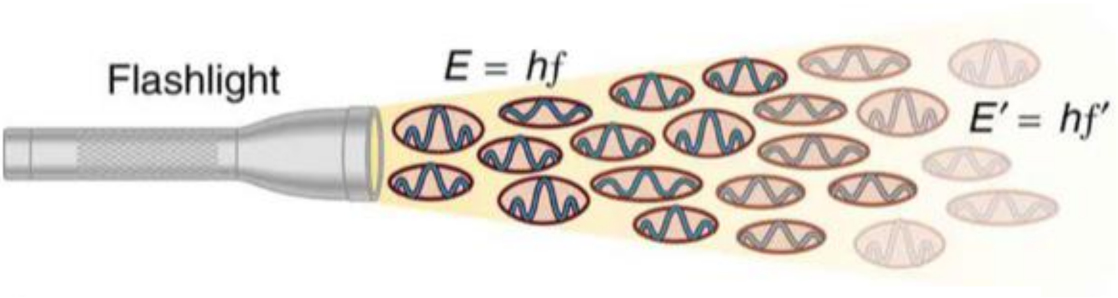
Explain the photoelectric effect using the idea of light quanta or photons **(STEM_GP12MPIVh-45).**

Explain qualitatively the properties of atomic emission and absorption spectra using the concept of energy levels **(STEM_GP12MPIVh-46).**

Calculating radioisotope activity using the concept of half-life **(STEM_GP12MPIVh-i-47)**

I. WHAT HAPPENED
PRE-TEST:

Directions: Observe the given picture below. After which, answer the questions that follow. Do this in your notebook/Activity Sheet.



Adapted from College Physics, Openstax

Figure 1. A flashlight emitting light

1. What have you observed in the illustration?
2. What does it imply?

II. WHAT I NEED TO KNOW
DISCUSSION

The Photoelectric Effect and Radioactivity

Light has a dual nature. You have learned that light is a wave based on its behavior and its properties. However, light cannot be considered merely as a wave because it behaves in ways that are not wave-like. Light must be understood to be a particle as well.

Photons as Particles of Light

All forms of electromagnetic waves, including light, have a dual nature. As they travel through space, they act as waves resulting in either interference or diffraction. These waves carry energy with them that enables them to propagate even without the aid of a medium. But as electromagnetic radiation interacts with atoms and molecules, the radiation beam acts like a stream of energy particles referred to as **photons or light quanta.** Each photon possesses an amount of energy dependent on the frequency f or wavelength λ of the radiation in the beam. This shows that electromagnetic radiation, light to be more specific, has a dual nature of being both a wave and a particle. This energy is mathematically determined as

$$\text{Photon of energy } = hf = \frac{hc}{\lambda}$$

In this equation, h is Plank's constant with the value of 6.626 x 10^{34} J s. **Planck's constant** is a physical constant widely used in the study of quantum mechanics, a branch of physics that focuses on the atomic level applications of physics.

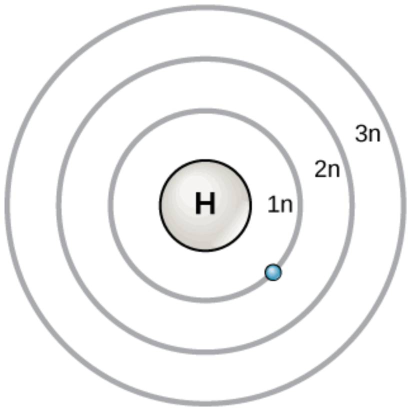
Big Idea:
Energy is needed by bodies in motion. As a wave, light propagates because of the energy of the waves. As a particle, light travels because of the energy possessed by each photon. In life, you need to store energy to be able to do your daily activities.

The Photoelectric Effect

Under certain conditions, when light is incident on a surface, electrons are ejected. These electrons receive the energy carried by the photons that hit the surface of the material. For any type of surface, light must have a sufficiently short wavelength to provide energy large enough to eject electrons. At the threshold or the maximum allowable wavelength (frequency), the energy of the photon must be equal to the amount of work necessary to free an electron from the surface of the material. This phenomenon is referred to as the ***photoelectric effect***. *It essentially describes how photons of light provide energy to the electrons of an atom to have it ejected.* Ordinary metals have threshold wavelengths within the ultraviolet range. The ultraviolet range includes electromagnetic waves that carry higher energies than visible light but less than that of X-rays.

Energy Levels, Atomic Emission, and Atomic Absorption

In Bohr's model of hydrogen (H) atom as shown in Figure 2 below, circular eletron orbits are assumed to surround the nucleus. The electrostatic force of attraction provides the centripetal force between the nucleus and the electrons in orbit, and the circular motion of the eletrons provides the centrifugal force that balances the centripetal force. The energy causing this force is said to be quantized or expressed using integers that correspond to the energy levels of the atom.

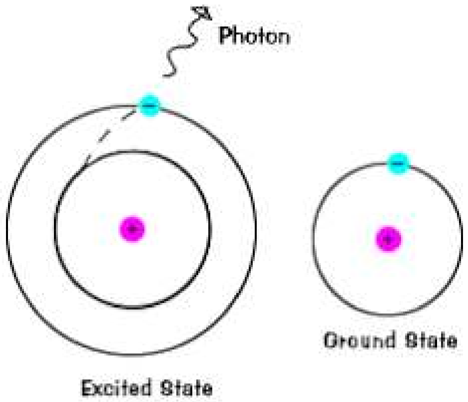


Adapted from https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Supplemental_Modules%28Physical_and_Theoretical_Chemistry%29/Electronic_Structure_of_Atoms_and_Molecules/Bohr_Diagrams_of_Atoms_and_Ions

Figure 2. An energy level diagram of Bohr's model of the H atom

Energy level diagrams provides a summary of the allowed energies for a system. Recall you understanding of quantum numbers in chemistry. The energy levels correspond to the ***principal quantum number*** that determines in which energy level or shell an electron is located.

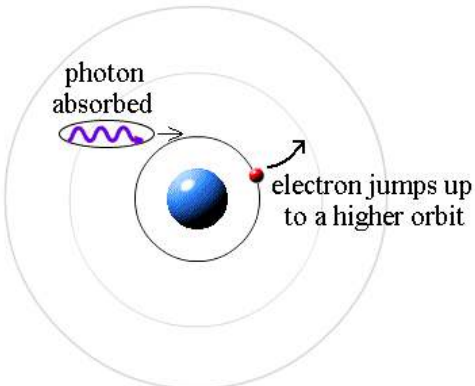
Consider an atom in the neutral state. If an electron falls closer to the necleus, its potential energy decreases and makes the energy of the atom negative. The grund state is the lowest possible state for any atom as characterized by the smallest possible orbit. See Figure 3.



Adapted from https://images_gsfc.nasa.gov/educators/lessons/xray_apectra/background-atoms.html

Figure 3. An atom that falls to a lower energy level releases energy that results in the emission of a photon

Whenever an isolated atom falls from a higher energy level to a lower energy level, an amount of energy is released from the electron, resulting in the emission of a photon. This particle carries the energy lost by the atom as it transitions to the lower energy state. On the other hand, when an atom absorbs a photon, an electron in one of its energy levels will absorb the energy possessed by the photon. This will result in the atom being raised to one of its allowed energy levels.



Adapted from https://physics.weber.edu/carroll/honors/failures.htm

Figure 4. An atom that absorbs a photon also absorbs its energy, resulting in the atom to increase its energy level

Visible Light

The range of photon energies for **visible light** from red to violet is *1.63 to 3.26 eV*, respectively. These energies are on the order of those between outer electron shells in atoms and molecules. This means that these photons can be absorbed by atoms and molecules. A *single* photon can actually stimulate the retina, for example, by altering a receptor molecule that then triggers a nerve impulse. Photons can be absorbed or emitted only by atoms and molecules that have precisely the correct quantized energy step to do so. For example, if a red photon of frequency f encounters a molecule that has an energy step, ΔE, equal to hf, then the photon can be absorbed. Violet flowers absorb red and reflect violet; this implies there is no energy step between levels in the receptor molecule equal to the violet photon's energy, but there is an energy step for the red.

There are some noticeable differences in the characteristics of light between the two ends of the visible spectrum that are due to photon energies. Red light has insufficient photon energy to expose most black-and-white film, and it is thus used to illuminate darkrooms where such film is developed. Since violet light has a higher photon energy, dyes that absorb violet tend to fade more quickly than those that do not. Take a look at some faded color posters in a storefront some time, and you will notice that the blues and violets are the last to fade. This is because other dyes, such as red and green dyes, absorb blue and violet photons, the higher energies of which break up their weakly bound molecules. (Complex molecules such as those in dyes and DNA tend to be weakly bound.) Blue and violet dyes reflect those colors and, therefore, do not absorb these more energetic photons, thus suffering less molecular damage.

Transparent materials, such as some glasses, do not absorb any visible light, because there is no energy step in the atoms or molecules that could absorb the light. Since individual photons interact with individual atoms, it is nearly impossible to have two photons absorbed simultaneously to reach a large energy step. Because of its lower photon energy, visible light can sometimes pass through many kilometers of a substance, while higher frequencies like UV, x-ray, and rays are absorbed, because they have sufficient photon energy to ionize the material

Radioactivity

In 1896, Henri Becquerel accidentally discovered that uranyl potassium sulfate crystals emit an invisible radiation that can darken a photographic plate when the plate is covered to exclude light. After a series of expriements, he concluded that the radiation emitted by the cystals was of a new type, one that requires no external stimulation and was so penetrating that it could darken protected photographic plates and ionized gases. This process of spontaneous emission of radiation by uranium was soon to be called ***radioactivity***.

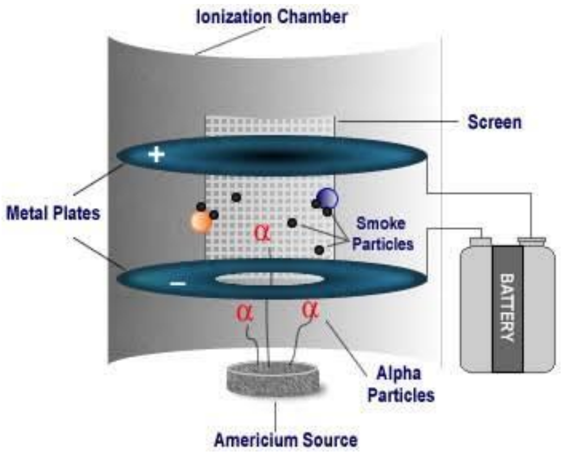
Subsequent experiments by othe scientists showed that other substances were more powerfully radiactive. The most significant investigtaions of this type were conducted by ***Marie and Pierre Curie.*** After several years of careful and laborious chemical separation processes on tons of pitchblende, a radioactive ore, the Curies reported the discovery of two previously unknown elements, both radioactive. These were named *polonium* and *radium*. Subsequent experiments, including Rutherford's famous work on alpha-particle scattering, suggested that radioactivity is the result of the *decay,* or disintegration, of unstable nuclei.

Three types of radioactive decay occur in a radioactive substance: alpha (α) decay, in which the emitted particles are He nuclei; beta ($\boldsymbol{\beta}$) decay , in which the emitted particles are either electrons and positrons; and gamma ($\boldsymbol{\gamma}$) decay, in which the emitted "rays" are high-energy photons. A positron is a particle like the electron in all respects except that the position has a charge of $+e$ (in other words, the positron is the antimatter twin of the electron). The symbol e^- is used to designate an electron, and e^+ designates a positron.

The three types of radiation have quite different penetrating powers. ***Alpha particles*** barely penetrate a sheet of paper, ***beta particles*** (electrons and positrons) can penetrate a few millimeters of aluminum, and ***gamma rays*** can penetrate several centimeters of lead.

The Smoke Detector

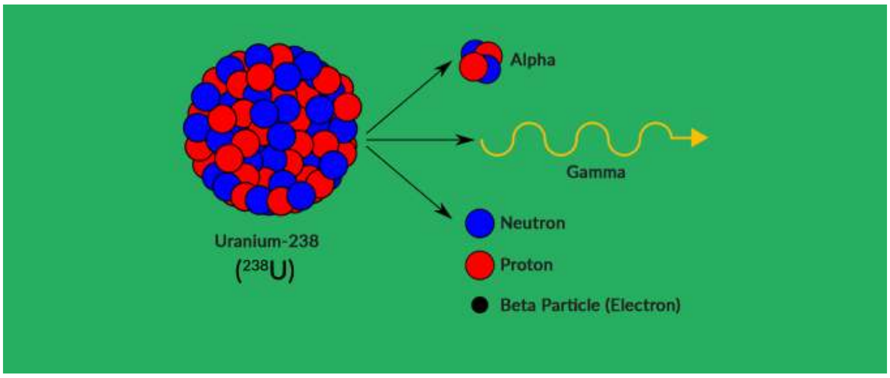
A life-saving application of alpha decay is in the household smoke detector. Most of the common ones uses a radioactive material. The detector consists of an ionization chamber, a sensitive current detector, and an alarm. A weak radiactive source (usually $^{241}_{95}9Am$) ionizes the air in the chamber of the detector, creating charged particles. A voltage is maintained between the plates inside the chamber, setting up a small but detectable current in the external circuit. As long as the current is maintained, the alarm is deactivated. However, if smoke drifts into the chamber, the ions becomes attached to the smoke particles. These heavier particles do not drift as readily as do the lighter ions, which causes a decrease in the detector current. The external circuit senses this decrease in current and sets off the alarm.



Adapted from https://www.epa.gov/radtown/americium-ionization-smoke-detectors

Figure 5. How a smoke detector works

Radioactive Decay and Half-life



Adapted from https://earthhow.com/radioactive-decay-isotopes/

Figure 6. How radioactive decay occurs for an unstable isotope of uranium

Every atom contains a nucleus and its core with a radius of about 10^{15} m. The nucleus is made up of protons and neutrons, collectively called ***nucleons***. The nuclear force holds the nucleus together. This force of attraction is stronger than the force of repulsion between pairs of protons. This force of attraction between the nucleons decreases rapidly with particle separation and is essentially inexistent for nucleons that are more than 5×10^{15} m apart.

Big Idea:

The nuclear force of attraction is greater than the electrostatic force of repulsion among the protons of an atom.

Naturally occuring nuclei heavier than lead are usually radioactive; many artificially produced elements that are lighter are also radioactive. A radioactive nucleus spontaneously ejects one or more of its particles to transform into a different nucleus. This process of particle ejection corresponds to the **radioactive decay** of the nucleus. It is termed "decay" because the process transforms or changes ejected particles into a nucleus of an element.

Radioactive decay entails the release of energy in the form of radiation. The stability of a radioactive nucleus with respect to its spontaneous decay is measured by its half-life $T_{\frac{1}{2}}$. **Half-life** is defined as the amount of time in which half of any sample of identical nuclei will undergo decomposition. This means that after the period specified by the half-life of the substance, only half of the remaining amount will be left. This process continues indefinitely because the amount of the material can oly become negligible, but not non-existent. The half-life is constant for each isotope.

A simple relation exists between the number of atoms of radioactive material present N and the number of atoms that will decay (ΔN) in a short time (Δt). This relationship is given by

$$\Delta N = \lambda N \Delta t$$

In this equation, λ is referred to as the decay constant , which is related to the half-life as given by,

$$\lambda T_{\frac{1}{2}} = 0.693$$

The quantity $\frac{\Delta N}{\Delta t}$ is referred to as the activity of the sample or the **rate of disintegrations** in the sample. This means that the sample steadily decreases with time and is measured using the unit becquerel (Bq). Note that 1 Bq = 1 decay(s).

Example 1:

Cobalt-60 (^{60}Co) is usually used as a radiation source in the practice of medicine. This isotope of cobalt has a half-life of 5.25 years. How long will it take for its activity to decrease to about one-eighth its original amount?

Solution:

In each half-life, only half of the sample decays remain. Note that

$$\left(\frac{1}{2}\right)\left(\frac{1}{2}\right)\left(\frac{1}{2}\right) = \frac{1}{8}$$

Three half-lives or 15.75 years should pass for the sample to decay so that one-eighth of its original amount will remain.

Example 2:

Radium has a half-life of 1620 years. Determine how many radium atom decay in 1 s in 1 g of its sample. The atomic weight of radium is 226 kg/mol.

Solution:

One gram of a sample has 0.001/226 kg/mol. Thus, 1g of radium contains

$$N = (1g)\left(\frac{0.001\frac{kg}{mol}}{22\ g}\right)\left(6.02\ x\ 10^{26}\ \frac{atoms}{\frac{kg}{mol}}\right)$$
$$\approx 2.66\ x\ 10^{21}\ atoms$$

The decay constant is computed as follows:

$$\lambda = \frac{0.693}{(1620\ years)(3.16\ x\ 10^{7}\ \frac{s}{year})} \approx 1.35\ x\ 10^{-11}\ s^{-1}$$

Then, you have

$$\frac{\Delta N}{\Delta t} = \lambda N = (1.35\ x\ 10^{-11}\ s^{-1})\ (2.66\ x\ 10^{21}\ atoms)$$
$$\approx 3.6\ x\ 10^{10}\ s^{-1}$$

One gram of radium disintegrates by an amount of approximately $3.6\ x\ 10^{10}$ atoms per second.

Performance Task:

Directions: Observe the illustration below. After which, answer the given question.

Figure 7. A poster with some colors fading

Question: Why do the reds, yellows, and greens fade before the blues and violets when exposed to the Sun, as with this poster? Relate your answer to the idea of photon energy.

III. WHAT I HAVE LEARNED
EVALUATION/POST TEST

I. **Multiple Choice**: Choose the letter of the correct answer. Write it on your notebook/Answer Sheet.

1. As the electromagnetic radiation interacts with atoms and molecules, the radiation beam acts like a stream of energy particles referred to as __________________.
   a. Photons or light quanta
   b. Ultraviolet rays
   c. X-rays
   d. Radioactive decay
2. Which of the following statement is INCORRECT?
   a. Photoelectric emission does not occur below the threshold frequency.
   b. The photoelectric current increases with the frequency of incident light.
   c. Threshold frequency does not depend on the metal used.
   d. The emission of photoelectrons is an instantaneous process.
3. The phenomenon of photoelectric effect is _______.
   a. Adiabatic process
   b. Instantaneous process
   c. Isothermal process
   d. Spontaneous process
4. Consider an atom in the neutral state. If an electron falls closer to the nucleus, its potential energy _____________.
   a. Decreases
   b. Increases
   c. becomes neutral
   d. none of the choices
5. Whenever an isolated atom falls from a higher energy level to a lower level, an amount of energy is released from the electron, resulting in the emission of a _____________.
   a. Proton
   b. Neutron
   c. electron
   d. photon
6. Which of the following statement is NOT true about half-life?
   a. It is the amount of time in which half of any sample of identical nuclei will undergo decomposition.
   b. After a period specified by the half-life of a substance, only one fourth of the original amount of the substance will remain.
   c. The half-life is constant for each isotope.
   d. All of the above.
7. The household smoke detector is a life-saving application of _________.
   a. Alpha decay
   b. Beta decay
   c. Gamma decay
   d. Carbon dating

8. All radioactive sources have a life-life. Which statement about half-life of a source is correct?
   a. It is half the time for the radioactive source to become safe.
   b. It is half the time it takes for an atom to decay.
   c. It is half the time it takes the activity of the source to decrease to zero.
   d. It is the time it takes the activity of the source to decrease by half.
9. A radioactive sample has a half-life of 5.0 min. What fraction of the sample is left after 20 min?
   a. ½
   b. ¼
   c. 1/8
   d. 1/16
10. What happens to the half-life of a radioactive substance as it decays?
   a. It remains constant.
   b. It increases.
   c. It decreases.
   d. It could do any of these.

II. Problem Solving: Answer the given problems below. Show the solution in your notebook (10 points each).

1. Consider cobalt-60 (^{60}Co) with a half-life of 5.25 years. How many years will it take for its activity to decrease to one-fourth of its original amount?
   a. Given:
   b. Formula:
   c. Solution:
   d. Final answer with unit:
2. Consider radium, which has a half-life of 1620 years. How many atoms of radium will decay in 5 s in 15 g of its sample? Consider the atomic weight of radium to be 226 kg/mol.
   a. Given:
   b. Formula:
   c. Solution:
   d. Final answer with unit:

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SYNOPSIS AND ABOUT THE AUTHOR

Light propagates as a particle in the form of photons. These particles possess energy that allow light to travel in a straight line. When these particles get in contact with a material, the photoelectric effect results, wherein electrons are ejected from the surface of the material.

Each atom has an associated set of energy levels that explain the phenomena of atomic emission and atomic absorption. Emission takes place when an electron moves from a higher energy level to a lower energy level, thus releasing photons from the atom. Absorption takes place when an electron moves from a lower energy level to a higher energy level by absorbing photons.

Radioactive materials are heavy elements that have unstable nuclei. Half of the sample of these elements decay after each half-life of the element.

ANSWER KEY

Pre-Test:

1. Answers may vary.
2. An EM wave of frequency f is composed of photons, or individual quanta of EM radiation. The energy of each photon is $E = hf$, where h is Planck's constant and f is the frequency of the EM radiation. Higher intensity means more photons per unit area. The flashlight emits large numbers of photons of many different frequencies, hence others have energy $E' = hf'$, and so on.
1.

Evaluation/Post-Test:

I. Multiple Choice:

1. A	6. B
2. C	7. A
3. B	8. D
4. A	9. D
5. D	10. A

II. Problem Solving:

1. For each half-life of cobalt 60, only half of the sample decays will remain. Note that
$$\left(\frac{1}{2}\right)\left(\frac{1}{2}\right) = \left(\frac{1}{4}\right)$$
Two half-lives or 10.5 years should pass for the sample of the substance to decay to one-fourth of its original amount.
2. One gram of a sample contains (0.001/226 kg/mol). Thus, 15g of radium contains
$$N = (15g)\left(\frac{\frac{0.001kg}{mol}}{226\ g}\right)\left(6.02x10^{26}\frac{atoms}{\frac{kg}{mol}}\right)$$
$$\approx \mathbf{4.00\ x\ 10^{22}\ atoms}$$
Computing for the decay constant, you have
$$\lambda = \frac{0.693}{(1620\ years)(3.16\ x\ 10^{7}\frac{s}{year})} \approx 1.35\ x\ 10^{-11}s^{-1}$$
Then, you have
$$\frac{\Delta N}{\Delta t} = \lambda N = (1.35\ x\ 10^{-11}s^{-1})(4.00\ x\ 10^{22}\ atoms)$$
$$\approx 5.4\ x\ 10^{11}s^{-1}$$
Fifteen grams of radium disintegrate by an amount of approximately 5.4 x 10^{11} atoms per second.

Rowena R. Dinokot graduated Bachelor of Secondary Education – Major in Biology at Jose Rizal Memorial State College, Katipunan Campus, Katipunan, Zamboanga del Norte last 2008. She also finished the degree Master of Arts in Education major in Administration and Supervision at Foundation University, Dumaguete City last 2018. Presently, she is teaching at Demetrio L. Alviola National High School (SHS Department) as Class Adviser of XII-STEM where she handled Sciences and Research.

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