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An introduction about synchrotron light for high school teachers

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Abstract: This article is motivated by the Sirius School for High School Teachers (ESPEM) and the lack of texts on synchrotron light and its application in basic education. It is aimed at high school teachers of Natural Sciences (Physics, Chemistry and Biology) and aims to present an introduction to the concept of synchrotron radiation, in the largest scientific enterprise in Latin America, the National Center for Research in Energy and Materials (CNPEM), where the newest Brazilian synchrotron light source is located, in a particle accelerator called Sirius. After introducing the reader to the development of Brazilian science, the present work's methodology is to address the conceptual definition and history of synchrotron light, for its understanding in a qualitative way and to generate results that are in dialogue with the application of modern and contemporary physics in basic education, and concluding with the presentation of ideas that dialogue with the content present in school curricula on how to approach these concepts in basic education, which dialogues with the application of Modern and Contemporary Physics in High School.
Keywords: synchrotron light; teachers; accelerators; high school teachers

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Introduction

This article is an introductory text dedicated to high school teachers, explaining the underlying science of synchrotron radiation and describing its main properties. The motivation for this article was the Sirius School for High School Teachers (ESPEM) (Acioly, 2020), (Acioly, 2021), held annually since 2019. During ESPEM, selected teachers are immersed in a national research environment with content at the forefront of knowledge, experiencing various parts of Brazil's largest scientific infrastructure, the Brazilian Center for Research in Energy and Materials (CNPEM) (2022). This complex of laboratories houses Sirius, the new Brazilian synchrotron light source and the country's largest particle accelerator, in addition to four major national laboratories of great national and international relevance: the National Synchrotron Light Laboratory (LNLS), the National Nanotechnology Laboratory (LNNano), the National Biosciences Laboratory (LNBio), and the National Bio-renewables Laboratory (LNBR).

This professional training course for basic education teachers lasts one week and is carried out through a partnership between CNPEM and the Brazilian Society of Physics (SBF). Throughout the week, teachers tour the laboratory facilities and understand the importance of the research conducted at CNPEM. Additionally, they are introduced to research by CNPEM researchers and external guests, with a didactic approach, so that they can bring what they have learned back to their cities, incorporating ideas from modern and contemporary physics into basic education classrooms. After participating in this continuing education course and immersing themselves in the atmosphere of Brazilian research at the forefront of knowledge, teachers are invited to become promoters of CNPEM's and Sirius's research, as well as the technological advancements of Brazilian science in their schools.

This article is divided into five parts. After this introduction, Section 2 introduces the concept of synchrotron radiation. Section 3 presents a historical review of synchrotron radiation, while Section 4 discusses current synchrotron light sources. Finally, we present some suggestions for classroom approaches.

Method

Inspired by Brazilian scientific production, one of its objectives is to build knowledge about synchrotron light to later propose strategies on how to apply this content in basic education, being a tool for high school physics teachers.

What is Synchrotron Light

In 1054 CE, a supernova that produced the Crab Nebula, located in the constellation Taurus about 2 kiloparsecs (1 parsec = 3.26 light-years) from Earth, was observed by the Chinese (Mayal, 1962), although the connection between the supernova and the nebula was made centuries later. In 1731, the English physician and amateur astronomer John Bevis identified the nebula and linked it to the supernova reported by the Chinese in 1054 (Margaritondo, 2022). Part of the luminosity emitted by this nebula is synchrotron radiation. This nebula emits a huge amount of synchrotron radiation, covering a wide frequency range, including the visible spectrum. Many astronomers observed synchrotron radiation for centuries, long before its detection in accelerators.

By synchrotron light, we understand the electromagnetic radiation emitted by a charge moving at relativistic speed and undergoing acceleration perpendicular to its velocity, possessing polarization properties. Synchrotron radiation is emitted by a charge moving in an arc determined by a deflecting magnetic field. This radiation is observed in extragalactic sources, such as the Crab Nebula. It is also produced on Earth in synchrotron light laboratories. Synchrotron radiation does not follow the same emission pattern as blackbody radiation; it is non-thermal. Unlike blackbody radiation, its intensity increases at lower frequencies. It also exhibits characteristic polarization in the plane perpendicular to the magnetic field around which the charges are spiraling. Synchrotron radiation has a broad spectrum of typical frequencies. This spectrum can be modified by varying the curvature of the trajectory. Thanks to its unique properties, synchrotron light has become a research tool in various fields of science.

All phenomena of classical electromagnetic radiation, whether synchrotron or not, are implicitly included in Maxwell's four equations, which state that accelerated electric charges emit electromagnetic radiation. In 1865, James Clerk Maxwell published his study (Maxwell, 1865), predicting electromagnetic waves traveling at the speed of light. In 1873, Maxwell formulated his equations, giving rise to classical electromagnetism (Maxwell, 1873).

Thus, the emission of synchrotron radiation, in which charged particles in curved orbits are subjected to acceleration perpendicular to their velocity, is based on Maxwell's equations. Synchrotron radiation is produced in the magnets that bend the beam or in special insertion devices (in wigglers or undulators). In all cases, the electron beam is subjected to the Lorentz force, thus emitting radiation.

The physical properties of synchrotron radiation are based on the fact that the charge moves at relativistic speed relative to the observer. The four important properties of synchrotron radiation are: (1) the fourth-power relationship between the power emitted by a relativistically moving charged particle, with acceleration perpendicular to its velocity, and its energy/mass ratio, i.e., $P \sim (E/mc^2)^4$; (2) the spectral distribution of this emission; (3) the geometry of the radiation, particularly its angular collimation and coherence; and (4) the polarization of the radiation. These characteristics were described by Julian Schwinger, whose theory was fundamental to understanding synchrotron radiation in 1947 (Schwinger, 1949). In other words, the main characteristics of synchrotron radiation were derived well before 1905, the year Albert Einstein published his paper on relativity. In 1897, Joseph Larmor's formula linked the emission of an electric charge to the square of its acceleration (Eq. 1).

$$P = \frac{\mu_o q^2 a^2}{6\pi c} \quad (1)$$

Where μ_0 is the magnetic permeability of the vacuum, q the particle's charge, a the magnitude of its acceleration, and c the speed of light in a vacuum. The power, Eq. 1, is a Lorentz invariant, meaning it is independent of the observer. However, Larmor's formula is valid for particle velocities much less than the speed of light in a vacuum (v << c), being exact for v=0. But why electrons (or positrons) and not protons? The rate of radiation emission by an accelerated charged particle is given by Larmor's formula (Eq. 1) and depends on the square of the product of the particle's charge and its acceleration. According to Newton's second law, the centripetal acceleration due to the Lorentz force is inversely proportional to the particle's mass; that is, the greater the mass, the smaller the acceleration for a given force. Thus, electrons or positrons have a higher rate of radiation emission compared to protons.

Larmor postulated the existence and named the electron years before its discovery. In 1898, Alfred-Marie Liénard derived the properties of synchrotron radiation from Maxwell's equations (Liénard, 1898). To handle his derivations, he invented mathematical tools that are still used today and obtained Liénard's formula.

$$P = \frac{\mu_o q^2 \gamma^6}{6\pi c}\left(a^2 - \left|\frac{\vec{v}\times\vec{a}}{c}\right|^2\right)$$

$$onde$$

$$\gamma \equiv \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} \qquad (2)$$

The factor γ^6 implies that the radiated power increases enormously as the electron's velocity approaches the speed of light. Both Larmor's expression, Eq. 1, and Liénard's expression, Eq. 2, are Lorentz invariants. This is because the energy emitted in the electron's frame of reference ΔU radiated in the time interval Δt is measured by the observer in the laboratory as ΔU'=ΔU in the time interval Δt'=Δt. Thus, power, being the ratio between energy and the time interval, remains invariant. The factor γ, as we will see later, is equal to the electron's energy divided by its rest energy mc2≈511 keV. For GE's 100 MeV cyclotron (next section), γ≈200. In the old UVX synchrotron light source at the National Synchrotron Light Laboratory (LNLS) in Campinas, the ring energy was 1.37 GeV, so γ≈2700. For SIRIUS, with 3 GeV, γ≈6000. Thus, the emitted power (Eq. 2) is very high.

The reason relativity is not necessary to derive the theory of synchrotron radiation is that Maxwell's equations are implicitly relativistic. For example, the invariance of the speed of light explicitly emerges from Maxwell's wave equation, which predicts its value without specifying the frame of reference. It is important to emphasize that Einstein did not discover but accepted this invariance, even though it seemed counterintuitive (Margaritondo, 2022).

History of Synchrotron Radiation

For a recent review on the history of synchrotron light, see (Margaritondo, 2022). Synchrotron radiation, produced in a non-natural way, was first observed accidentally at the 100 MeV synchrotron of General Electric (GE) in Schenectady, New York. Currently, at synchrotron radiation facilities that focus on producing such radiation, such as SIRIUS and the old UVX at the National Synchrotron Light Laboratory (LNLS, 2022), electrons are stored in a circular accelerator (called a storage ring, see next section). The GE scientists were looking for radiation from their betatron. The goal was to assess the possible impact of radiation on the accelerator's operation and performance. Part of the team believed that electrons circulating in a closed orbit were a constant current and could not emit radiation, while others believed the radiation would be very weak (Margaritondo, 2022).

In fact, centripetal acceleration in classical mechanics is the square of the tangential velocity, v, divided by the radius of curvature, R, i.e., $a = \frac{V^2}{R}$. The radius of the GE betatron was relatively large, so the acceleration and its square were small. The team ignored relativistic effects. For the emitted power, one must use Lorentz's relativistic transformations from the electron's frame of reference (strictly, the inertial frame moving instantaneously with the electron at velocity v) relative to the laboratory. The angular velocity of the electrons circulating in the betatron, i.e., the cyclotron frequency (not to be confused with synchrotron), W_c= v/r, obtained from Newton's Second Law, is given by

$$\left|-e\vec{v}\times\vec{B}\right|=\frac{mv^2}{R}$$

$$eB=m\omega_C$$

$$\omega_C=\frac{evB}{m} \tag{3}$$

According to Eq. 3, the values for GE's cyclotron were in the radio wave range. Thus, the GE team used radio wave detectors and found nothing. They did not realize, based on Schwinger's yet-to-be-published results, that the frequencies could extend to much higher values, including visible light, however, the visible radiation was blocked by an opaque window.

The temporal width of the radiation pulse emitted by the electron determines the spectrum of synchrotron radiation. For example, since Δtmeasured by the observer is very small, when transformed to frequencies (Fourier Transform), the frequency spectrum Δf is very large. Regarding the emitted frequencies, the relativistic cyclotron frequency in the electron's frame of reference is

$$\omega_C=\gamma\frac{evB}{m} \tag{4}$$

and not the value in Eq. (3). This is because relativity replaces the magnetic field with an electric field of magnitude E = γ B which alters the cyclotron frequency from Eq. (3) to Eq. (4). This frequency, however, is the value in the electrons' instantaneous frame. In the laboratory frame, the frequency is lower by a factor ≈2 γ , due to the relativistic Doppler effect caused by the motion of the source (electron) relative to the observer.

First Generation Synchrotrons

The first generation of synchrotron radiation sources were called "parasitic facilities" due to the perception of the initial users of these facilities, high-energy physicists, towards the "intrusive" synchrotron radiation users. That is, first-generation synchrotron light sources were essentially light lines built in existing facilities designed for nuclear and particle physics studies.

One of these first-generation sources was the Synchrotron Ultraviolet Radiation Facility (SURF) in Washington in 1961. The goal was to explore the possibility of using synchrotron light as a source for ultraviolet spectroscopy. The establishment of SURF marked the beginning of the first generation of synchrotron radiation facilities.

Second Generation Synchrotrons

Second-generation synchrotron light sources are those dedicated to producing synchrotron radiation and employed electron storage rings to harness synchrotron light, such as the old UVX at LNLS.

The first accelerator entirely dedicated to synchrotron radiation experiments, Tantalus, in Wisconsin, was inaugurated in 1968. There was then a massive growth in the use of synchrotron radiation through various generations of synchrotron sources and free electron lasers, starting from the 1970s, due to the advent of storage rings. In a storage ring, the electron beam has a very long lifetime, typically eight to twelve hours, allowing users to work in the vicinity for many hours.

Third Generation Synchrotrons

Third-generation synchrotron light sources optimize light intensity by incorporating long straight sections in the storage ring to insert insertion devices, such as wigglers and undulators, as in the case of SIRIUS in Campinas.

Initially, undulators and wigglers were inserted into older storage rings, and in some cases, second-generation rings were designed with the possibility of incorporating insertion devices. However, synchrotron users demanded a new generation of storage rings with long straight sections for undulators, allowing for higher brightness and greater spatial coherence. With increased brightness, it is possible to achieve better spatial and temporal resolutions.

Third-generation facilities specialize in high-energy X-rays (above 5 keV, known as hard X-rays), large diameter rings (850 to 1440 meters in circumference), or soft X-rays (between 100 eV and 1000 eV), smaller diameter rings. The range between 1000 eV and 5000 eV is called intermediate energy X-rays. The European Synchrotron Radiation Facility (ESRF) in Grenoble was the first of the third-generation hard X-ray sources to operate with a 6 GeV storage ring in 1994, followed by the Advanced Photon Source at Argonne National Laboratory (7 GeV) in late 1996, and SPring-8 (8 GeV) in Harima Science Garden City in Japan in 1997. These machines are physically large with the capacity for 30 or more insertion devices in addition to deflection magnets.

Main Components of a Synchrotron Accelerator

The first dedicated synchrotron facilities, known as second-generation synchrotrons, began operation in the 1970s. Initially, physicists and chemists were the primary users. Today, synchrotron facilities are utilized by users from various fields, including archaeologists, environmental scientists, biologists, art restoration specialists, astrophysicists, among others. Figure 1 presents the main components of a synchrotron accelerator.

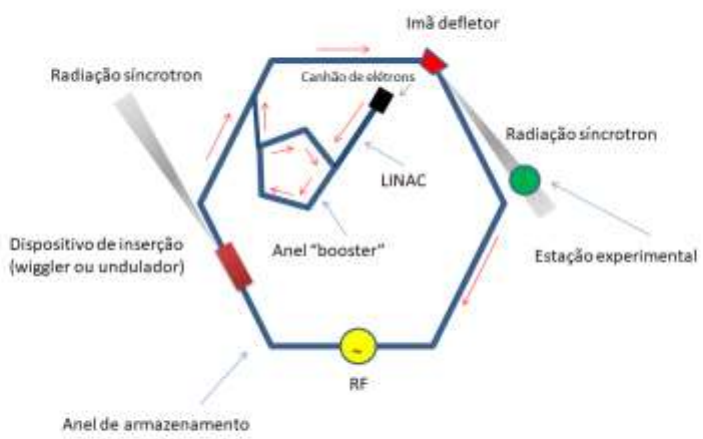

Figure 1. Main components of a synchrotron accelerator (see text for details). The red arrows indicate the direction of electron beam propagation.

A synchrotron accelerator consists of five main components (Figure 1): i) an electron source; ii) a booster ring; iii) a storage ring; iv) a radiofrequency (RF) source; v) several beamlines. The electron source is known as an "electron gun." Electrons are accelerated by a linear accelerator (linac) to tens of MeV, typically 100 MeV. Then, the electrons are injected into the booster ring where they are injected and accelerated again to reach a near or equal to final energy. The electrons are then periodically injected into the storage ring to maintain it. The storage ring keeps the electron beam in a closed orbit using various magnets. The magnets are usually of three types: a) dipole or bending magnets cause a change in the electron's trajectory to achieve a closed orbit; b) Quadrupole magnets are used to focus the electron beam to compensate for Coulomb repulsion between electrons; c) sextupolemagnets correct chromatic aberrations (electrons with slightly different energies) that arise from focusing by the quadrupoles.

Insertion devices are a general term for a series of magnetic elements that can be added to a storage ring, as illustrated in Figure 2. They are designed to provide radiation whose characteristics are improved compared to that available from dipole magnets. In insertion devices (wigglers and undulators, Figure 2), they are based on the fact that magnetic fields deflect moving charges (Lorentz's Law). A magnetic field applied perpendicular to the charge's movement will produce acceleration. As illustrated in Figure 2, the electron beam oscillates relative to the observer in the laboratory, emitting radiation due to its acceleration. In both cases, both in the wiggler and the undulator, there is a succession of magnetic dipoles, so that the electron zigzags. The magnetic fields alternate with spacing characterized by λB of the order of a few centimeters, so that the electron oscillates with a wavelength also given by λB. The frequency of the observed pulses has a frequency of νB=c/(λB), which is of the order of 10 GHz. Undulators represent an advancement over wigglers for lower magnetic fields, a larger number of magnetic poles, and shorter λB lengths.

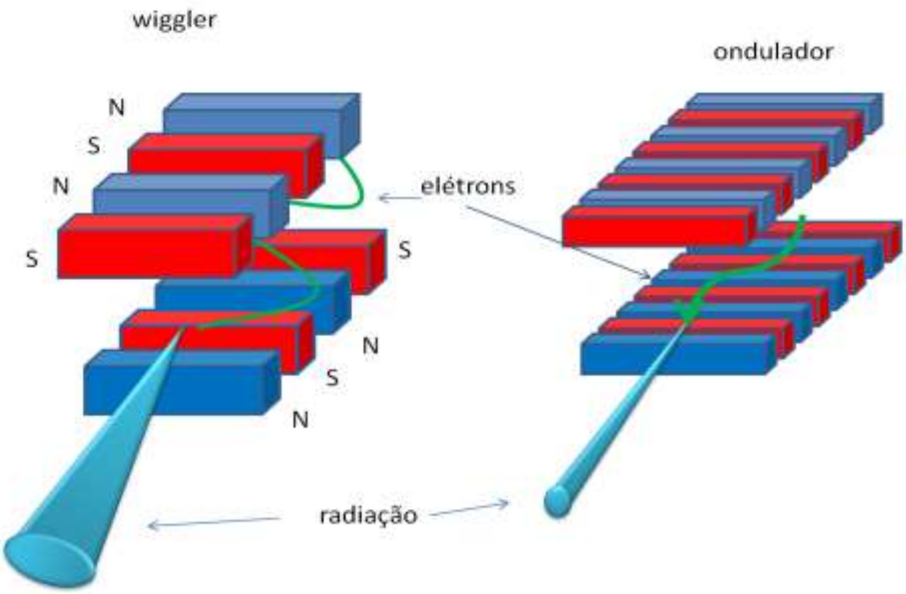

Figure 2. Insertion devices: wiggler (left) and undulator (right). Note: in various reference documents, the terms "onduladores" and "unduladores" have the same meaning

The electrons in the storage ring have kinetic energies on the order of GeV, thus possessing relativistic speeds. The total energy of an electron moving with relativistic energy is given by

$$E = \frac{mc^2}{\sqrt{1-\frac{v^2}{c^2}}} = \gamma mc^2 \qquad (5)$$

Where $\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$ is the Lorentz factor.

While its kinetic energy (the difference between its total energy and rest energy) is given by

$$K = E - mc^2 = mc^2(\gamma - 1)$$

$$\gamma >> 1$$

$$K \cong E$$
$$\gamma \cong \frac{K}{mc^2} \tag{6}$$

The ring is a structure consisting of arc sections containing bending magnets, and straight sections used for insertion devices (wigglers and undulators) (Fig. 2), which generate more intense synchrotron radiation. The bending magnets used to deflect the electrons connect the straight sections, often used to provide synchrotron radiation.

The electrons (with charge q = -e) spinning with a period $T = \frac{2\pi R}{v}$ in the storage rings are deflected in a circular orbit by the Lorentz force, which in the low-speed limit is given by

$$\left| -e\vec{v} \times \vec{B} \right| = \frac{mv^2}{R} \tag{7}$$

Where R is the radius of the ring. However, since the electron's speed is relativistic, we need to perform a generalization and using v » c, we have

$$ecB = \gamma \frac{mc^2}{R} \tag{8}$$

We then find the relationship between the radius of the ring, R, the magnetic field, and the electron beam energy K.

$$R = \frac{\gamma K}{ecB} \tag{9}$$

Energy is lost by the electrons due to synchrotron radiation emission. This energy must be supplied to the electron beam so that they do not spiral out, colliding with the inner walls of the storage ring. This is achieved by a radiofrequency (RF) source (see Fig. 1), which provides the electron beam with just the right amount of extra energy each time it passes through it. Finally, beamlines are positioned tangentially to the storage ring, along the axes of insertion devices (wigglers and undulators) and tangentially to the bending magnets. The first section of a beamline, referred to as the 'front end,' has several functions and safety features—it isolates the vacuum of the beamline from the vacuum of the storage ring, and monitors the position of the photon beam. It also defines the angular acceptance of synchrotron radiation through an aperture, blocking spurious x-rays and Bremsstrahlung radiation. The beamline also filters out the low-energy portion of the synchrotron radiation spectrum, which is heavily absorbed by matter and can damage optical components. The beam is then typically focused.

Results and Discussion

Some Suggestions for Basic Education Teachers to Relate the Concepts Present in Synchrotron Light Sources to High School Students' Curricular Content

The use of methodologies with experimental demonstrations (Araújo, 2003) and conceptual analogies (Santos, 2013), especially in the areas of science teaching, make teaching activities more attractive for students of any school level. There is a consensus among researchers in the field of education regarding the need to include modern and contemporary physics in high school (Pessanha & Pietrocolla, 2017), and the application of synchrotron light in basic education aligns with the need to bring applied research content closer to the curricular content. According to Chevallard (1991), the need to adapt scientific knowledge for pedagogical and educational purposes, in order to make connections between different types of knowledge, defines the concept of didactic transposition. He stated that the term "didactic transposition" was initially used by the French sociologist Michel Verret, in his doctoral thesis "Le temps des études," published in 1975. This article proposes possible ways for the application and assistance for basic education teachers, using didactic transposition to relate concepts present in synchrotron light sources that resonate with the high school curriculum (Brasil, 2006).

As there are many physics concepts involved in synchrotron light sources, we have selected the following concepts: circular motion, diffraction grating, waves and oscillations, theory of relativity, magnetic field, electric field, electromagnetic radiation beyond the visible spectrum: ultraviolet and infrared, and the photoelectric effect.

A very useful tool for introducing complex phenomena is analogy (Santos, 2013), and there are already analogies with synchrotron light in the literature (Acioly, 2023). Several authors have discussed the potential of using analogies in science teaching. An analogy is a comparison based on similarities between structures of two different knowledge domains, one known and one unknown. For example, one of the first applications of the interaction of radiation with matter is the photoelectric effect. There are suggestions in the literature on how to introduce the photoelectric effect to high school students (Barretto, 2022; Kovacevic, 2006; Whalley, 2005). Below we present some strategies, using analogies, for teaching synchrotron radiation in high school.

The Path Traveled by Synchrotron Radiation/Light: Car Making Circular Movements with Headlights On

Accelerated charges emit radiation. However, for effective radiation emission to occur, it is necessary for energy, in the form of photons, to be transported over large distances from the charge. Only a fraction of the energy flux produced by the charge manifests as radiation. Part of this energy accompanies the charge along its trajectory. Machado (2006) suggests a visualization of this effect. Consider flies around a garbage bag. As we move the bag slowly, the flies will follow it. But as we move it faster, some may move far away from the bag. The flies that remain around the bag are analogous to the portion of the electromagnetic field attached to the charge. The flies that distance themselves from the bag represent the radiation emitted by the charge. To illustrate the generation of synchrotron light, we can use analogies. For example, a car with its headlights on, when making a turn, illuminates a certain region. The path traveled by the light, in the tangent, is the representation of synchrotron radiation, when a beam of relativistic electrons curves due to the dipole. Fig. 3 shows the geometry of synchrotron radiation in two situations: in part A, the geometry of the radiation emitted by the accelerated charge when its velocity is much lower than the speed of light, essentially displaying a dipole component. In part B, the figure shows the angular collimation, with a small opening angle, when its velocity is comparable to the speed of light. In this case, the radiation is analogous to a spotlight or headlight emitting radiation in the same direction of the electron's motion.

The characteristics of synchrotron radiation depend on two parameters: the angular frequency W_0 (i.e., the number of turns the electrons make in the ring per second), and the energy of the electrons in the storage ring, given by the Lorentz factor, γ . Here, the instructor can explore contents such as circular motion, change of reference frame within the context of Special Relativity, and wave propagation.

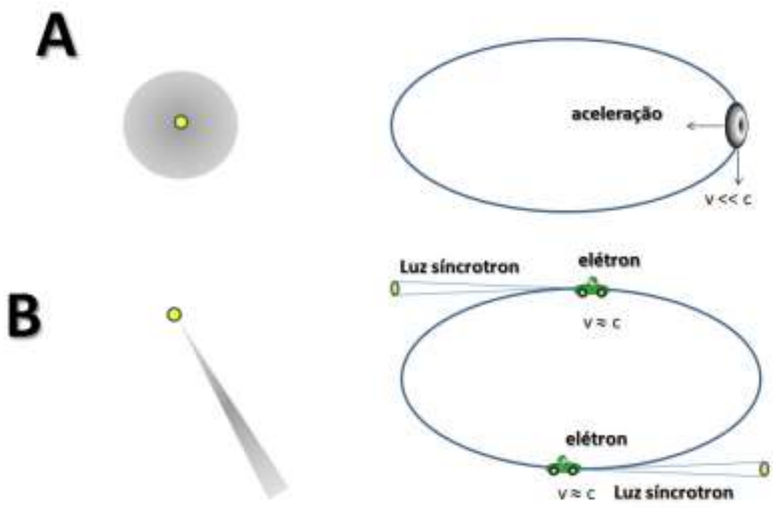

Figure 3. Emission patterns of an electron in a circular orbit: a) a) v/c <<1 . b) v ~c .The angular opening of the radiation cone decreases with the increase of the Lorentz factor, through the relation $\theta = 1/\gamma$

Monochromatization: Using CDs and DVDs as Diffraction Gratings

In school curricula (Brasil, 2006), phenomena such as reflection and diffraction are present in the daily lives of students and become relatively attractive due to the various easily understandable examples. Monochromatization (Fig. 4) is a phenomenon that involves both concepts. To bring some of the contents applied in a synchrotron light source closer to school content, one can think of a specific part of synchrotron radiation, X-rays.

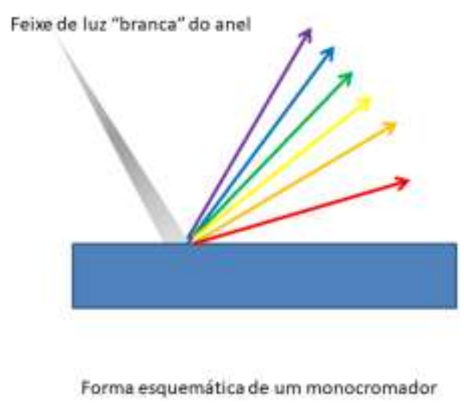

Figure 4. Diagram of a Monochromatization Process

To illustrate the monochromatization of X-rays, this work presents the use of CDs and DVDs by basic education students as a didactic strategy for understanding the concepts of reflection and diffraction gratings.

The underside of a CD/DVD has elements called "pits" or "lands," which are valleys or elevations throughout the material. When spun at a certain speed and in contact with the reader, these elements can send data to the computer. These "pits" function as slits, and a large set of slits is called a diffraction grating.

When monochromatic light is incident on a diffraction grating, or when white light (various wavelengths) is incident on the underside of a CD/DVD, it is decomposed into all colors, each in a different direction, as shown in Figure 4. The idea of using CDs and DVDs as diffraction gratings is already well-utilized in the literature (Kettler, 1991; Catelli, 2010) as an application of didactic transposition.

Atomic Absorption: A Mass-Spring System

In introductory Modern Physics courses, it is common to discuss atomic absorption through the interaction of a classical oscillator with electromagnetic radiation, showing how spectral lines arise (Santos, 2020; Velloso, 2020). We can consider a very simple model of an electron bound to an atomic nucleus and subjected to the action of an incident photon. In a classical model, we could represent the electron subject to a central Coulomb force due to the nucleus. This electron has its own (natural) frequency due to the nucleus, which also acts as a restoring elastic force. The electron-nucleus system forms an oscillating dipole, giving rise to a radiation field due to the oscillation of the accelerated electron. However, we know that an accelerated charge emits radiation. Thus, the electron must be subject to an additional force known as radiation reaction, analogous to a damped oscillator. For high school, we suggest using the mechanical analogue, the forced and damped mass-spring system, as illustrated in Figure 5.

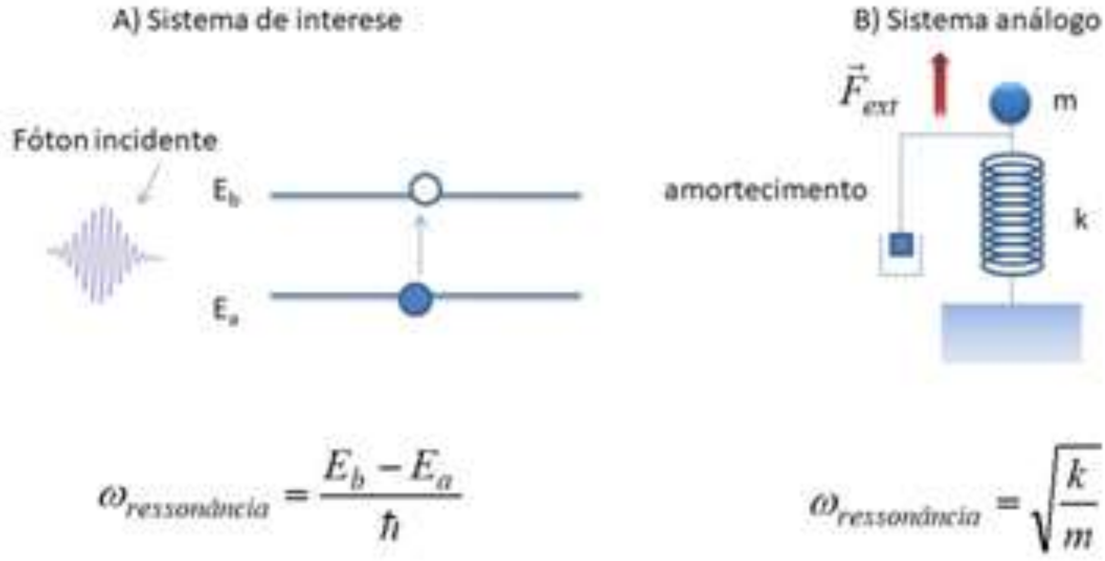

Figure 5. a) Resonant atomic absorption process. When the frequency of the incident photon matches the resonance frequency of the atomic system, absorption occurs. b) The mechanical analogue: A mass-spring system with its characteristic frequency, forced by an external force (analogous to the incident photon) and damped.

A path that can be applied in high school for damped and forced oscillations, a topic traditionally used only in higher education courses, is found in the literature in various works with suggestions for using low-cost materials such as timers, pendulums, and free software (Bonventi, 2015; Ferreira, 2005; Santos, 2013). The construction of these concepts needs to be a sequence of wave content (Brasil, 2006), where the teacher will work on amplitude, period, and frequency, then moving on to simple harmonic motion, to then introduce damped and forced oscillations.

Teaching Relativity

Newtonian physics, which can be summarized between mechanics, thermodynamics, and electromagnetism, have certain limits that are exceeded when certain variables, such as velocity, reach their maximum value. These limitations are present in school curricula and in teacher training difficulties (Ivani, 2010; Antonowiski, 2017).

As in synchrotron light sources, the speeds of the electrons are relativistic, there will be a transformation of the other quantities involved, such as space contraction and temporal dilation. For this, there is a need for a conceptual change from Newtonian physics, which is traditionally studied in school curricula (Brasil, 2006).

For the teaching of special relativity for high school, we recommend different approaches to physics teaching. Starting with the historical construction of Einstein's thought, described by Renn (2005), where each phase of scientific thought and the break with classical science is investigated: the experimentation phase, the theorization phase, and the reflection phase. We continue with the introduction to the application of activities for teachers in a series of didactic articles (Huggins, 2011a; Huggins, 2011b; Huggins, 2011c; Huggins, 2011d; Behroozi, 2014; Carr, 2009; Ruby, 2009).

As a suggestion, to expand access to materials for applying relativity in high school, we suggest the activities proposed by the Perimeter Institute for Theoretical Physics, in Canada, translated to Brazil by the International Center for Theoretical Physics of South America (ICTP-SAIFR),whose headquarters are located at the Institute of Theoretical Physics (IFT). These materials present activity proposals to understand the functioning of GPS, demonstrating time dilation and different references with accessible language for high school students (ICTP-SAIFR, 2022; Perimeter Institute, 2022).

Conceptual, Historical, and Experimental Approach to Electric and Magnetic Fields to Represent Electron Movement in the Synchrotron

For the conceptual approach that dialogues with high school content, it is necessary to make coherent approximations and analogies with the concepts. For there to be an initial acceleration in synchrotron light sources, electrons need to be immersed in electric fields. For these electrons to be aligned and able to make changes in the propagation direction, they need to be immersed in magnetic fields.

As a suggestion for building concepts of electric and magnetic fields, we suggest the use of historical approaches (Magalhães, 2002) and the construction of low-cost experiments (Moraes, 2019; Macedo, 2016). Some of these works suggest methodologies for teaching high school students the contents of accelerated particles in particle accelerators and colliders, which can be used in synchrotron light sources, such as Sirius and in particle colliders, such as LHC (Sinflório, 2006), (Wiener, 2016).

Electromagnetism is usually part of the content of the last year of high school (Brasil, 2006), and therefore the representation of how electrons curve in particle accelerators can be related to the magnetic force between magnets and low-cost ferromagnetic materials, such as clips or coins. Circular particle accelerators are usually polygons with many sides, in a sequence of straight and curved segments. In the time intervals when the electrons make the curves, they do so with very high speeds, in the case of relativistic and approximately constant modulus, which connects with the high school content of Uniform Magnetic Field generated by a charge in Uniform Circular Motion.

"Seeing" Light Beyond the Visible: Infrared and Ultraviolet

Research that uses synchrotron radiation analyzes the range of the electromagnetic spectrum that is comprised between infrared, passing through visible light and ultraviolet radiation, ending in X-rays. For illustration of this application, of how to detect radiation that is not visible to the human eye, we suggest some proposals for high school students to understand some characteristics of part of the electromagnetic spectrum, which are the invisible radiations that are on the border in the visible spectrum, based on previously published works (Micha, 2011; Soga, 2020; Alvarenga, 2005).

With certain electronic devices becoming increasingly accessible, such as cell phones and old webcams, the detection of infrared radiation becomes easily understandable. From analyzing the light emitted by remote controls pointed at cell phones to removing the infrared filter present in webcams. High school students can practice a small instrumentation by disassembling computer cameras and reassembling them without their filters that block the passage of infrared light. With this, these cameras start to detect most of the infrared spectrum, which makes them detect even a resistor connected to the power outlet, starting to see heat (Micha, 2011).

Aiming to bring the science involved in synchrotron light sources closer to the school audience, and as ultraviolet radiation is part of several studies in synchrotron-type accelerators, this article makes two application proposals for this part of the spectrum. The first is to dispel some myths about cell phone devices that emit radiation in the ultraviolet range, as has been said in fake news that do not deserve reference. The work carried out by Soga (2020) proposes an experimental study on Black Light, which partly emits UV radiation, and confirms that cell phone flashlights do not emit UV light, reassuring users. Another proposal that brings UV light closer to high school applications is the construction of cameras that detect UV, with low-cost and easily accessible materials, as proposed by Alvarenga (Alvarenga, Saliba, Milagres, 2005).

Conclusion

In conclusion, integrating the concepts of synchrotron light and modern physics into high school curricula can significantly enhance students' understanding of contemporary scientific advancements. By bridging these advanced topics with basic education, teachers can inspire a deeper interest in the natural sciences and foster a new generation of scientifically literate individuals.

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