REVISTA OWL (*OWL Journal*)
www.revistaowl.com.br – ISSN: 2965-2634

THREE-DIMENSIONAL MODELS FOR VISUALIZING THE QUANTUM STATES OF THE HYDROGEN ATOM: AN INSTRUCTIONAL APPROACH TO TEACHING MODERN PHYSICS

MODELOS TRIDIMENSIONAIS PARA A VISUALIZAÇÃO DOS ESTADOS QUÂNTICOS DO ÁTOMO DE HIDROGÊNIO: UMA ABORDAGEM INSTRUCIONAL PARA O ENSINO DE FÍSICA MODERNA

DOI: 10.5281/zenodo.22716242

Elvis Santos de Araujo[1]
Iurgan Henrique Cruz de Macedo[2]
Márcio Augusto Campos Pompermaier[3]
Artur Vitório Andrade Santos[4]
Mauro Guilherme Ferreira Bezerra[5]
Laffert Gomes Ferreira da Silva[6]
Moacy José Stoffes Junior[7]
Clever Reis Stein[8]

ABSTRACT

The teaching of Modern and Contemporary Physics at the secondary school level presents significant challenges, particularly because many of its concepts involve a high degree of abstraction and are commonly represented through mathematical formulations, symbolic representations, and two-dimensional illustrations. In this context, this study presents the development of three-dimensional instructional models designed to represent the quantum states of the hydrogen atom and to support the teaching and learning of Modern Physics. The models were developed by selecting quantum-mechanical concepts amenable to three-dimensional representation, followed by digital modeling

1 E-mail: elvis.santos@estudante.ifro.edu.br.
2 E-mail: iurgan.henrique@estudante.ifro.edu.br.
3 E-mail: pompermaier@msn.com.
4 E-mail:artur.santos@ifro.edu.br.
5 E-mail: mauro.guilherme@ifro.edu.br.
6 E-mail: laffert.silva@ifro.edu.br.
7 E-mail: moacy.stoffes@ifpr.edu.br.
8 E-mail: clever.stein@ifro.edu.br.

using three-dimensional design software and fabrication through 3D printing with polylactic acid (PLA) filament at an internal infill density of 20%. The resulting physical models represent different quantum states of the hydrogen atom and provide a tangible representation of spatial probability distributions associated with the electron. The models can be manipulated and examined from different perspectives, establishing a direct connection between mathematical and theoretical descriptions and their corresponding spatial representations. The proposed instructional resource is intended to support teachers in addressing abstract concepts related to atomic structure, quantum states, and quantum numbers. By enabling students to observe and manipulate three-dimensional representations of the hydrogen atom, the models may facilitate spatial visualization, strengthen conceptual understanding, and promote more meaningful learning experiences. The proposed approach therefore offers a potentially useful and accessible resource for incorporating Modern and Contemporary Physics into secondary education.

Keywords: Modern Physics; Quantum States; 3D Printing.

RESUMO

O ensino de Física Moderna e Contemporânea no nível de ensino médio apresenta desafios significativos, particularmente porque muitos de seus conceitos envolvem um alto grau de abstração e são comumente representados por meio de formulações matemáticas, representações simbólicas e ilustrações bidimensionais. Nesse contexto, este estudo apresenta o desenvolvimento de modelos instrucionais tridimensionais projetados para representar os estados quânticos do átomo de hidrogênio e para apoiar o ensino e a aprendizagem de Física Moderna. Os modelos foram desenvolvidos a partir da seleção de conceitos da mecânica quântica passíveis de representação tridimensional, seguida pela modelagem digital com software de projeto 3D e pela fabricação via impressão 3D com filamento de ácido polilático (PLA) e densidade de preenchimento interno de 20%. Os modelos físicos resultantes representam diferentes estados quânticos do átomo de hidrogênio e oferecem uma representação tangível das distribuições de probabilidade espacial associadas ao elétron. Os modelos podem ser manipulados e examinados sob diferentes perspectivas, estabelecendo uma conexão direta entre as descrições matemáticas e teóricas e suas correspondentes representações espaciais. O recurso instrucional proposto visa apoiar os professores na abordagem de conceitos abstratos relacionados à estrutura atômica, aos estados quânticos e aos números quânticos. Ao permitir que os alunos observem e manipulem representações tridimensionais do átomo de hidrogênio, os modelos podem facilitar a visualização espacial, fortalecer a compreensão conceitual e promover experiências de aprendizagem mais significativas. A abordagem proposta oferece, portanto, um recurso potencialmente útil e acessível para a incorporação da Física Moderna e Contemporânea ao ensino médio.

Palavras-chave: Física Moderna; Estados Quânticos; Impressão 3D.

INTRODUCTION

Modern Physics has emerged as one of the most influential and transformative fields of science, giving rise to groundbreaking discoveries and driving technological advances that have profoundly reshaped society. Its theoretical framework has provided explanations for phenomena that had previously remained elusive, while its applications have become essential across a wide range of fields, including medicine (Strikman et al. (2014)), telecommunications, computing, and space exploration (SCHECHTER, 1986). This scientific and technological impact, however, extends well beyond its historical contributions. Modern and Contemporary Physics remains at the forefront of scientific advancement, driving cutting-edge research and fostering the development of innovative technologies (SHABAJEE; POSTLETHWAITE, 2004).

Despite its significance, Modern and Contemporary Physics continues to receive limited attention in many secondary education contexts. Traditionally, physics instruction at this level has focused predominantly on Classical Physics, encompassing topics such as Mechanics, Thermodynamics, Wave Phenomena, and Electromagnetism, while subjects including Relativity, Quantum Physics, Nuclear Physics, Particle Physics, and Cosmology are often relegated to the later stages of the curriculum. Such curricular organization may hinder the development of a broader and more contemporary understanding of physics (GRIFFITHS; SCHROETER, 2018).. The effective integration of Modern and Contemporary Physics into the secondary school curriculum is therefore essential to students' scientific education and should be regarded as an important issue within educational discourse (SCHECHTER, 1986).

Although researchers in the field have advocated its inclusion in basic education for several decades, its implementation continues to face challenges related to teacher education, the availability of instructional materials, the time allocated to these topics, and the conceptual complexity inherent in areas such as Quantum Physics, Relativity, Nuclear Physics, and Particle Physics (OLIVEIRA et al., 2007; GOULART; LEONEL, 2022). Recent literature reviews indicate that, despite the growing number of proposals aimed at incorporating Modern Physics into secondary education, substantial challenges remain regarding teaching conditions and the selection of pedagogical strategies capable of facilitating students' understanding of concepts that often involve a high degree of abstraction (JANUÁRIO; HOERNIG; MASSONI, 2024). Furthermore, analyses of instructional materials used in secondary education suggest that the mere inclusion of these topics does not, in itself, ensure their effective pedagogical treatment, highlighting the need for resources and methodologies that promote contextualization and foster conceptual understanding (PEREIRA; GUERINI, 2023).

In this context, the use of diverse instructional and technological resources can broaden the possibilities for teaching these topics and contribute to more meaningful learning, particularly when such resources facilitate connections between abstract concepts and visual representations of physical phenomena (BICALHO; COSTA, 2024). Among these resources, three-dimensional models are particularly promising, as they can facilitate the representation of structures and phenomena whose visualization is challenging when conveyed solely through equations, symbolic representations, or two-dimensional images. Studies on the teaching of atomic orbitals, for example, have shown that three-dimensional models can enhance the visualization of spatial structures and support students' understanding of concepts related to electronic structure and quantum numbers (MARIN; SANTOS JÚNIOR; BIANCHI, 2017).

Against this backdrop, the present study aims to present the development of three-dimensional models for representing the quantum states of the hydrogen atom, conceived as instructional resources to support teachers in teaching Modern Physics, particularly topics related to atomic structure and the quantum description of the atom. The proposed approach is motivated by the need to translate mathematical and theoretical representations into tangible, spatially explorable objects, thereby enabling a more intuitive visualization of the characteristics associated with different quantum states (SHANKAR, 1994).

MATERIALS AND METHODS

The development of the three-dimensional instructional models began with the selection of content that could be meaningfully represented in three-dimensional space. Following this selection, the structures were digitally modeled using three-dimensional design software, enabling the detailed construction of the corresponding virtual models. This stage leveraged the capacity of 3D printing technology to accurately reproduce the fine features incorporated into the digital designs, thereby ensuring a high degree of fidelity between the virtual models and the resulting physical objects.

Upon completion of the modeling phase, the virtual models were fabricated using polylactic acid (PLA) filament, a material widely used in 3D printing owing to its mechanical strength, dimensional stability, and ease of handling. The internal infill density was set at 20%, providing sufficient rigidity and structural stability to meet the requirements of the proposed instructional application.

Finally, the printed models were made available for use in experimental activities. The provision of physical objects corresponding to representations commonly found in textbooks may contribute to more meaningful learning experiences by establishing a tangible connection between abstract representations and their physical counterparts. Through direct observation and manipulation of the models, students may develop more robust mental representations of the structures under study, thereby establishing cognitive connections that can be revisited and further developed in subsequent learning activities involving the same content.

RESULTS AND DISCUSSION

In the teaching of Earth and Natural Sciences, experimental activities that reproduce the phenomena under investigation play a fundamental role in supporting students' conceptual understanding. This approach becomes particularly challenging when addressing Modern Physics, as the abstract nature of its theoretical framework often requires students to engage in a higher degree of mental visualization and conceptual imagination. This challenge is widely recognized by teachers, teacher educators, and researchers in the field, who emphasize that the effective integration of Modern Physics into science education requires methodological adaptations and the development of accessible instructional strategies capable of promoting meaningful learning.

Within this context, representations of the quantum states of the hydrogen atom were selected for development as three-dimensional instructional models. This choice was motivated by the potential of physical three-dimensional representations to facilitate students' understanding of the behavior of the hydrogen atom across different quantum states. By providing a tangible representation of structures that are otherwise described primarily through mathematical formulations and abstract representations, the models are intended to support the visualization and conceptual interpretation of the corresponding quantum states.

In simplified form, the Schrödinger equation that describes the dynamics of the hydrogen atom can be expressed as follows (ZETTILI, 2022):

$$\Psi(r,\theta,\phi)=R(r)P(\theta)\Phi(\phi)$$

Here, R(r) is associated with the radial extent of the orbital, corresponding to the average distance between the electron and the nucleus. This component is related to the energy of the state, which varies as a function of the principal quantum number, n, which may take the integer values n = 1, 2, 3, 4, ….

The term P(θ) is associated with the shape of the orbital (i.e., the orbital type). These spatial shapes are determined by the orbital angular momentum quantum number, l, which specifies the magnitude of the electron's angular momentum. For a given principal quantum number n, the allowed values of l are given by l = 0, 1, 2, …, n − 1.

The term Φ(ϕ) is associated with the orientation of the orbital in space and describes the spatial orientation of the angular momentum. Its allowed values depend on l and are specified by the magnetic quantum number, m, according to the relation −l ≤ m ≤ l. Figure 1 illustrates a simulation of the first atomic orbitals of the hydrogen atom. The luminous region represents the spatial distribution in which the probability of finding the electron is highest.

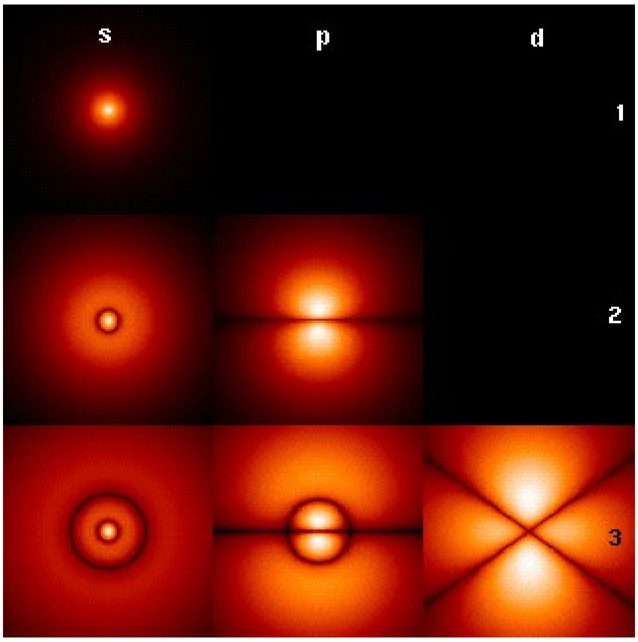

Figure 1. First atomic orbitals of the hydrogen atom: probability density for n = 1, 2, and 3 and l = s, p, and d. Note: m = 0. Source: (available at https://www.profpc.com.br/n%C3%BAmeros_qu%C3%A2nticos.htm).

Figure 2 presents the Px, Py, and Pz orbitals of the hydrogen atom. This representation facilitates a clearer visualization of the spatial geometry associated with the boundary conditions determined by the quantum numbers.

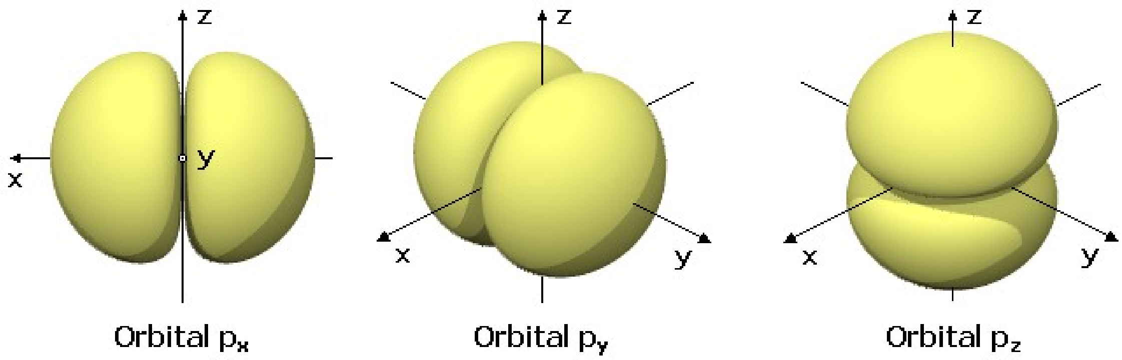

Figure 2. Three-dimensional representations of the px, py, and pz orbitals of the hydrogen atom, illustrating their spatial orientation. Source: (available at https://www.profpc.com.br/n%C3%BAmeros_qu%C3%A2nticos.htm).

These examples illustrate some of the ways in which this topic is commonly represented; however, its explanation is often based on abstract representations and conventional two-dimensional illustrations. To provide a more tangible means of representing the behavior of the hydrogen atom, three-dimensional models were developed to depict its electronic states. Figure 3, for example, represents the region of space in which the electron of the hydrogen atom, with a principal quantum number of 2, has the highest probability density of being found.

Figure 3. Three-dimensional didactic model fabricated using 3D printing, representing the spatial distribution of the probability density of finding the electron in the hydrogen atom for n=2n = 2.

In this context, the introduction of a physical model provides a more tangible and accessible representation of an otherwise abstract concept. By means of such a model, the behavior of the electron in a given energy state can be described and interpreted more intuitively. Figure 4 presents the three-dimensional models corresponding to other states of the atom.

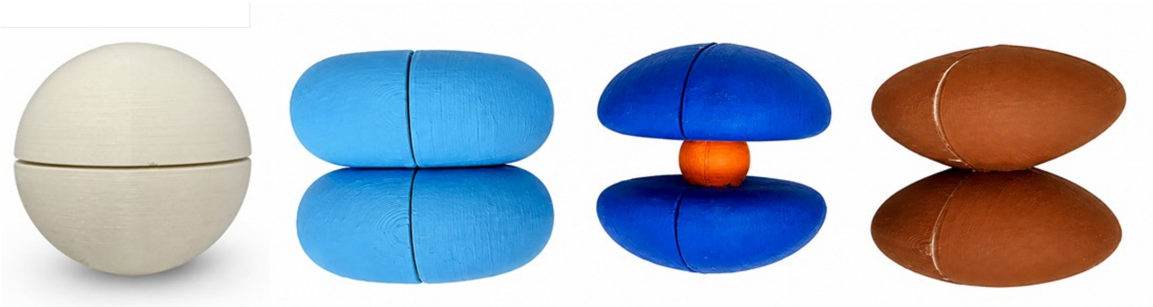

Figure 4. Three-dimensional didactic models fabricated using 3D printing, representing different spatial distributions of the electron probability density in the hydrogen atom.

As illustrated, the three-dimensional models can be handled, explored, and examined from different perspectives, thereby providing opportunities for a more comprehensive understanding than those afforded by conventional two-dimensional illustrations. Through direct interaction with the models, learners are no longer dependent solely on abstract representations; instead, they have access to a tangible reference that gives physical form to concepts described by the underlying theory. In this way, concepts that would otherwise remain largely abstract can be visually explored and physically manipulated, potentially facilitating the development of a deeper conceptual understanding of the phenomenon under study.

CONCLUSION

This study presented an instructional tool designed to support teachers in teaching and learning Modern and Contemporary Physics at the secondary school level. The successful implementation of this approach, however, requires effective pedagogical resources capable of providing concrete representations of otherwise abstract concepts. In this regard, the three-dimensional models fulfill an important instructional function by enabling students to visualize more clearly the different quantum states of the hydrogen atom as determined by the quantum numbers. By providing a structured and tangible representation of these states, the proposed models can facilitate students' conceptual understanding and promote more meaningful learning experiences, thereby contributing to more effective educational outcomes.

REFERENCES

BICALHO, A. C. M.; COSTA, M. O uso de TICs e a teoria da aprendizagem significativa no ensino de Física Moderna e Contemporânea: uma revisão de literatura. In: ENCONTRO NACIONAL DE APRENDIZAGEM SIGNIFICATIVA, 8., 2024, Caruaru. *Anais do 8º Encontro Nacional de Aprendizagem Significativa*. Campina Grande: Realize Editora, 2024.

GOULART, G. S.; LEONEL, A. A. Revisão da literatura sobre o ensino de Física Moderna e Contemporânea no Ensino Médio sob a ótica da TAS: problemáticas emergentes a partir de eventos brasileiros de ensino de Física. *Revista Dynamis*, v. 28, n. 1, p. 231-251, 2022. DOI: https://doi.org/10.7867/1982-4866.2022v28n1p231-251.

GRIFFITHS, D. J.; SCHROETER, D. F. *Introduction to quantum mechanics*. 3. ed. Cambridge: Cambridge University Press, 2018.

JANUÁRIO, M. D. A.; HOERNIG, A. F.; MASSONI, N. T. Tendências atuais sobre o ensino de Física Moderna: uma revisão de literatura. *Revista Educar Mais*, v. 8, p. 1-22, 2024. DOI: https://doi.org/10.15536/reducarmais.8.2024.3668.

MARIN, L.; SANTOS JÚNIOR, G. A.; BIANCHI, R. M. da C. Uma proposta para o ensino de orbitais atômicos no ciclo básico dos cursos de Engenharia a partir da construção de modelos tridimensionais utilizando materiais reutilizados. *Ensaios USF*, v. 1, n. 1, p. 238-246, 2017. DOI: https://doi.org/10.24933/eusf.v1i1.68.

OLIVEIRA, F. F.; VIANNA, D. M.; GERBASSI, R. S. Física moderna no Ensino Médio: o que dizem os professores. *Revista Brasileira de Ensino de Física*, v. 29, n. 3, p. 447-454, 2007. DOI: https://doi.org/10.1590/S1806-11172007000300016.

PEREIRA, P. do N.; GUERINI, S. C. Física moderna e contemporânea: análise de conteúdo dos livros didáticos de Física do Ensino Médio aprovados pelo PNLD de 2018. *Revista Contexto & Educação*, v. 38, n. 120, e10374, 2023. DOI: https://doi.org/10.21527/2179-1309.2023.120.10374.

PROF. PC. *Números quânticos*. [S. l.], [s. d.]. Disponível em: https://www.profpc.com.br/n%C3%BAmeros_qu%C3%A2nticos.htm. Acesso em: 16 ago. 2026.

SCHECHTER, B. Reports on subfields of physics: scientific interfaces and technological applications. *Physics Today*, v. 39, n. 4, 1986. DOI: https://doi.org/10.1063/1.881023.

SHABAJEE, P.; POSTLETHWAITE, K. *What happened to modern physics?* 2004.

SHANKAR, R. *Principles of quantum mechanics*. 2. ed. New York: Springer, 1994.

STRIKMAN, M.; SPARTALIAN, K.; COLE, M. W. *Applications of modern physics in medicine*. Princeton: Princeton University Press, 2014.

ZETTILI, N. *Quantum mechanics: concepts and applications*. 3. ed. Hoboken, NJ: John Wiley & Sons, 2022.

Recebido em: 18/08/2026
Aprovado em: 30/08/2026
Publicado em: 11/09/2026