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DETERMINING THE DENSITY AND MOLAR MASS OF AIR IN A HOME EXPERIMENT

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ABSTRACT

Formulation of the problem. Experimental research is an integral part of physics education. During distance learning, students can carry out hands-on experiments only at home. Modern smartphones, equipped with various sensors, offer significant capabilities for this purpose. The literature offers quite extensive descriptions of experiments aimed at determining mechanical, acoustic, and optical quantities using smartphones. At the same time, insufficient attention has been paid to determining gas parameters that can be measured using the pressure sensor embedded in smartphones. Therefore, the relevant task is to develop a methodology for experimenting to determine the density of air and its molar mass at home using a pressure sensor.

Materials and methods. To achieve the objective of the study, we used the analysis of the curriculum of the course "General Physics for Bachelor of Engineering", a review of the methodological instructions for performing laboratory work in the section "Molecular Physics and Thermodynamics" of the physics course of technical universities, a review of the literature on the topic of the study, and an analysis of the results of student research on the dependence of air pressure on altitude. We also surveyed students about the possibility of conducting the research at home and their interest in conducting other experiments using a smartphone.

Results. The methodology for determining the density and molar mass of air was developed based on the results of a study of the pressure-height dependence. It is shown that it is necessary to perform statistical processing of experimental data to estimate the sought quantities. The experimental results allowed us to obtain values of density and molar mass of air that show a good correlation with the tabulated values.

Conclusions. Studying the pressure-altitude relationship using a smartphone and the PhyPhox application allows for fairly accurate calculations of air density and molar mass. According to the survey results, students responded positively to conducting home experiments using smartphones.

KEYWORDS: *barometric formula; air density; smartphone; pressure sensor; home experiment; teaching physics.*

ВИЗНАЧЕННЯ ГУСТИНИ ТА МОЛЯРНОЇ МАСИ ПОВІТРЯ В ДОМАШНЬОМУ ЕКСПЕРИМЕНТІ

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АНОТАЦІЯ

Постановка проблеми. Невід'ємною складовою навчання фізики є проведення експериментальних досліджень. Під час дистанційного навчання натурний експеримент студенти можуть виконувати тільки вдома. Значні можливості для цього надають сучасні смартфони, які оснащені різноманітними датчиками. В літературі достатньо широко описані експерименти по визначенню механічних, акустичних та оптичних величин з використанням смартфона. У той же час, недостатньо уваги приділено визначенню параметрів газів, що можна здійснювати, використовуючи датчик тиску, які встановлений у смартфоні. Тому актуальним постає завдання розробки методики проведення експерименту по визначенню густини повітря та його молярної маси в домашніх умовах з використанням датчика тиску.

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Матеріали і методи. Для досягнення поставленої мети дослідження використано аналіз навчальної програми курсу «Загальна фізика для бакалаврів інженерних спеціальностей», огляд методичних вказівок до виконання лабораторних робіт з розділу «Молекулярна фізика і термодинаміка» курсу фізики технічних ВНЗ, огляд літератури за темою дослідження та аналіз результатів студентських досліджень щодо залежності тиску повітря від висоти. Також ми проводили опитування студентів стосовно можливості проведення домашніх дослідження та готовності до проведення інших експериментів з використанням смартфона.

Результати. Розроблена методика визначення густини та молярної маси повітря за результатами дослідження залежності тиску від висоти. Показано, що для коректного оцінювання шуканих величин необхідно проводити статистичну обробку експериментальних даних. Проведені експерименти дозволили одержати значення густини та молярної маси повітря, які добре корелюють з табличними значеннями.

Висновки. Дослідження залежності тиску від висоти із застосуванням смартфона і програми PhyPhox дозволяє достатньо точно обчислити густину і молярну масу повітря. За результатами опитування встановлено, що студенти схвально відносяться до виконання домашніх досліджень з використанням смартфона.

КЛЮЧОВІ СЛОВА: *барометрична формула; густина повітря; смартфон; датчик тиску; домашній експеримент; навчання фізики.*

INTRODUCTION

The problem statements. Studying physics at any level includes conducting educational experiments. As a result of their implementation, students receive direct confirmation of the principles of physics, acquire experimental skills, and develop critical thinking. According to the results of the study by Klein et al. (2021), this is most effective when students independently acquire experimental data. During distance learning, students can independently conduct research and process obtained data by working with real equipment in remote access mode or using available or home-made equipment. Mobile devices with a range of sensors offer significant opportunities for conducting physical experiments in both face-to-face and distance learning. (Sukariasih et al., 2019; Slipukhina et al., 2020). As emphasized by Milner-Bolotin & Milner (2023), and Cukierman et al., (2017), the use of smartphones in the educational process stimulates students' interest in scientific research and bridges the gap between first-year students and Engineering. The use of smartphones makes it quite easy to conduct research when students study the sections "Mechanics" (see, for example, Bug-Os et al. (2023)), "Electricity and Magnetism" Lincoln, (2024), Zhuang et al. (2023), "Oscillations and Waves" Sárközi (2023), Podlasov et al. (2023), Csernovszky et al. (2024). A detailed review of Experiments with mobile devices is presented by Kuhn & Vogt (2022), Imtinan (2023), and Colt et al. (2021).

At the same time, the literature is poorly represented by experiments that students can conduct in distance learning outside of educational laboratories to study the properties of gases, especially using mobile device sensors. Therefore, it may be of interest to develop a methodology for experimenting at home to determine the density of air and its molar mass.

The analysis of current research. In the scientific and methodical literature, practically no attention is paid to the experimental determination of the density and molar mass of air. Only the pumping method is described in the methodological instructions for laboratory works in physics for face-to-face education (see, for example, Golovina et al., 2013; Ruda, 2018). The essence of the method is to weigh the flask with air before and after pumping and measure the pressure change in the flask. Such an experiment can be performed only in a physics laboratory.

Another way to determine air density is to study the pressure-altitude dependence using an Arduino or Raspberry with a pressure sensor (for example, the GY-68 module has a pressure accuracy of up to 3 Pa, i.e., it can detect a change in altitude of 17 cm), or using a smartphone equipped with a pressure sensor, as suggested by Wye (2023). In his paper, Wye (2023) described the use of the iPhone 11. Measurements made with the PhyPhox app installed on the iPhone 11 allowed the author to calculate the air density with an accuracy of ± 0.03 kg/m^3, which is approximately 2.5% of the tabulated density value and corresponds to a pressure change of about 1.2 Pa. Perhaps such high accuracy is determined by the use of the iPhone itself. In smartphones of other manufacturers, there are fluctuations in the readings of the pressure sensor in the range of 2-5 Pa, which does not allow to reliably register small changes in pressure when climbing even one stair, not to mention changes in the height of a brick, as mentioned by the author. The procedure for determining the error of the pressure sensor is not described clearly in the paper.

Since most students do not have iPhones, it is necessary to develop a measurement procedure to investigate the relationship between pressure and altitude, taking into account the errors of pressure sensors in smartphones from other manufacturers.

The purpose of this article is to describe an experiment to determine the density and molar mass of air using only mobile devices and processing the obtained data.

THEORETICAL BASES OF THE RESEARCH

In general, the pressure-altitude relationship is described by the barometric formula:

$$P = P_0 e^{-\frac{Mgh}{RT}}, \qquad (1)$$

where P_0 is the pressure at the height h = 0, M is the molar mass of the gas, g - free fall acceleration, R - the universal gas constant, and T - the temperature.

Experimental verification of the formula (1) could, in principle, confirm the validity of the Boltzmann distribution and could be used to determine the molar mass of air, or the universal gas constant. However, when rising even to a height of ~50-60 m above the initial level (this corresponds to the height of an 18-20-storey building), taking into account the table values of the molar mass of air and other constant values for a temperature of 290 K, the exponent power is about $6 \cdot 10^{-3}$, which is significantly less than one. Taking into account the errors of the experiment, this does not allow us to determine the power factor in formula (1) with sufficient accuracy, therefore to calculate R or M.

Taking into account the smallness of the exponent, one can write $e^{-\frac{Mgh}{RT}} \approx 1 - \frac{Mgh}{RT}$ then

$$P = P_0\left(1 - \frac{Mgh}{RT}\right)$$

and pressure difference for two altitudes is

$$\Delta P = P_1 - P_2 = P_0\frac{Mg(h_2 - h_1)}{RT} = P_0\frac{Mg}{RT}\Delta h.$$

From the ideal gas equation of state

$$\frac{PM}{RT} = \rho, \qquad (2)$$

where ρ is the density of the gas. Assuming that the air density and temperature do not depend on the altitude, we obtain

$$\rho = \frac{\Delta P}{g\Delta h}. \qquad (3)$$

Equation (3) clearly shows that if the pressure is measured at different altitudes and a graph of $P(h)$ is constructed, then the tangent of its slope angle equals ρg, which allows you to calculate the air density. With known air density, temperature, and pressure from the equation of state of an ideal gas, we can obtain the molar mass:

$$M = \frac{\rho RT}{P}. \qquad (4)$$

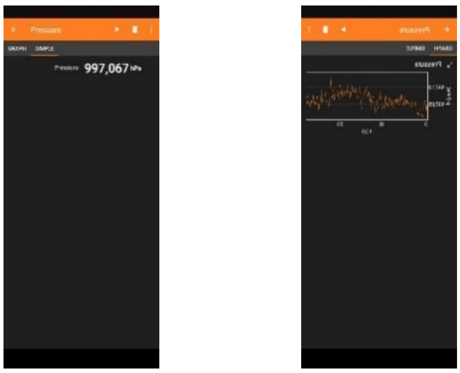
METHODS OF THE RESEARCH

To achieve the research objectives, we used an analysis of the general physics course syllabus for bachelor of engineering specialties, a review of the methodological instructions for laboratory work in the section "Molecular Physics and Thermodynamics" of the physics course at technical universities, a review of the literature on the topic of the study, and an analysis of the results of students' research on the dependence of air pressure on altitude.

RESULTS OF RESEARCH

Modern mobile smartphones, smartwatches, and tablets are equipped with various sensors, some of them includes a pressure sensor. To find out if a device has a pressure sensor and its specific characteristics (sensitivity, measurement range, and some others), you can use a program like Sensors Multitool or a similar one. The operation principle of the pressure sensor in mobile devices is similar to that of a membrane barometer. However, in this case, a tensor resistor is attached to the membrane, which is one of the arms of the Wheatstone bridge. The change in the deflection of the membrane results in a variation in the resistance of the strain gauge, thereby causing an imbalance in the Wheatstone bridge circuit. This imbalance is detected by the corresponding software and displayed on the gadget's screen. Processing of the pressure sensor signal is carried out by such free software as Sensors Multitool or PhyPhox, or by applications that simulate the appearance of a barometer on the screen of a mobile device. The Sensors Multitool software (Fig. 1) displays only instantaneous pressure values to the nearest hundredth of a hPa. In contrast, the PhyPhox software has two modes - displaying instantaneous pressure values with an accuracy of thousands of hPa (Fig. 2a) or a graph of pressure versus time (Fig. 2b). In this mode the data is accumulated and can be sent to a computer in MS Excel or CSV file format. In addition, the PhyPhox program can be controlled directly from the computer. Apps that display a barometer on a smartphone screen (Fig. 3) smooth out instantaneous pressure values and usually round them to tenths of a hectopascal (hPa). Note that these readings may differ significantly from laboratory membrane barometer readings and have a relatively large margin of error. Therefore, in our opinion, it is not advisable to use a "barometer" application in a smartphone to conduct experiments.

Fig. 1. Sensors Multitool screen.



a) b)

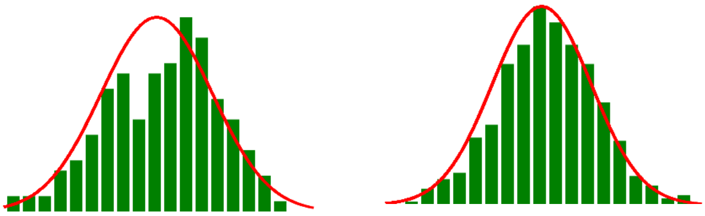
Fig. 2. PhyPhox screen.

Fig. 3. Barometer in smartphone.

Source: author's development.

The pressure sensor in electronic gadgets, like other sensors (acceleration, magnetic field), has 'noise' (fig. 2b), and its readings change rapidly over time, practically preventing the capture of instantaneous pressure values in applications like Sensors Multitool and PhyPhox. This noise can be one of the reasons for inaccuracies in the barometer readings on the smartphone screen.

In order to estimate the pressure value and the errors that can be assumed when determining it with PhyPhox, it is necessary to perform a statistical analysis of the pressure values recorded in it, namely to calculate the sample mean and standard deviation. For this purpose, we used the pressure values recorded by the PhyPhox program over 30 s and 45 s (300 and 450 values, respectively). Based on these data, we calculated the mean, the standard error and built he histograms of the distribution of the deviations from the mean (Fig. 4). The solid line on the figure, corresponding to a normal distribution with values of variance determined from the experimental data. It's clear that that the 'noise' of the pressure sensor is distributed nearly to a normal law. The standard error for the data shown in fig. 4 is 2.5×10^{-2} hPa and 2.3×10^{-2} hPa, respectively.



a) b)

Fig. 4. Histogram of deviations of instantaneous pressure values from the mean.
a) 30 s; б) 45 s.
Source: author's development.

The change of altitude of 20 cm (this is comparable to the standard step height of 15 cm in high-rise buildings) causes the air pressure to change by approximately 2.5 Pa, i.e. within the error of the measuring device. This means that reliably detecting a change in pressure can be achieved with a change in height of around 60-70 cm so that the pressure change exceeds the error by about three times. To construct a graph of the pressure-altitude relationship and determine air density 5-7 data points are sufficient. This corresponds to a change in height of 3-3.5 meters, which corresponds to a rise of one floor. Of course, increasing the height of the altitude reduces the error in plotting and the error in calculation of air density.

The task of determining the density and molar mass of air was proposed to students of the Institute of Thermal and Atomic Power Engineering at Igor Sikorsky Kyiv Polytechnic Institute (54 individuals). The task was optional, and only approximately half of the students completed it. The devices used by the students for measurements may be equipped with pressure sensors from different manufacturers with different resolutions and thus different errors. That's why, we recommend conducting the measurement procedure as follows: at each altitude, activate pressure measurements for 25-30 seconds using the PhyPhox program, and then send the obtained data to a computer using the "Export data" option. Alternatively, you can save the data on the gadget using the "Save experiment state" option for future use.

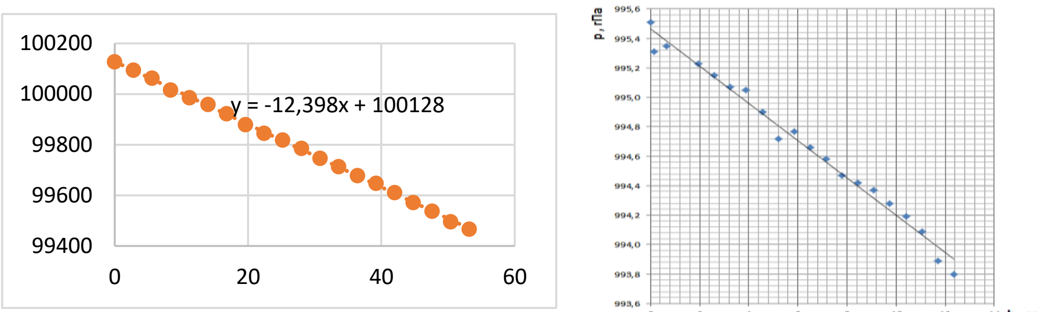
The processing of experimental data involves determining the statistical characteristics (mean and standard error) of a large dataset. For statistical parameters (mean values and errors) of a large number of exported experimental data, it is advisable to use mathematical packages such as MS Excel, Google Sheets, or use the program that was developed by us for such cases. This program is hosted on our website Physics.zfftt.kpi.ua within the Moodle environment and is accessible to registered users. In addition to the mean value and standard error, the program calculates other parameters of the statistical distribution and builds a histogram, an example of which is shown in Fig. 4.

Depending on where they lived, students had the opportunity to study pressure changes with height variations ranging from 6 meters (a two-story building) to 55 meters (a 20-story building). The largest number of experiments were conducted in 5- and 9-story buildings.

To plot the $P(h)$ dependence graph, it is convenient to use the Scatter Plot option of MS Excel with the construction of a trend line and display of the equation describing this line (fig. 5a). The multiplier before the function argument is the angular coefficient of the line is equal to the product $g\rho$. If students did not have access to MS Excel, they constructed the $P(h)$ graph using alternative software tools (Fig. 5b), or used graph paper to plot the graph and determined the slope coefficient manually. From the experimental results, the density values of air calculated by the students ranged from 1.17 to 1.28 kg/m³ with an error of ±0.1 kg/m³. These results are in good agreement with the data of the reference tables (see, for example, https://gutpfusik.blogspot.com/2020/07/blog-post.html), taking into account their dependence on the temperature and humidity of the air. Based on the experimental density values, students calculated the molar mass of air. Its values ranged from 27.8 g/mol to 30.4 g/mol with an error of up to ±2.4 g/mol. This range also reasonably corresponds to the tabulated value of 28.9 g/mol.

The lack of previous experimental experience and processing their results caused a number of questions that the students had. The most frequently asked questions were about how to use MS Excel to calculate the mean value and the error, and how to use the Scatter Plot. To answer these questions, we developed guidelines and posted them on the website physics.zfftt.kpi.ua.

At the end of the experiment, we surveyed students about their attitudes toward conducting home experiments and their reasons for not conducting the experimental investigation $P(h)$. The students who completed the research task were unanimous in their support for this type of work and expressed their satisfaction with getting acquainted with the capabilities of a smartphone as a measuring device. As for the students who were unable to complete the survey (28 out of 54), the main reason was the lack of a pressure sensor in their smartphones (23), lack of time (4), and personal reasons (1).



a) b)

Fig. 5. The examples of experimental dependences of pressure on altitude obtained by students.

Source: own research.

CONCLUSIONS AND PERSPECTIVES FOR FURTHER RESEARCH

Using a smartphone as a measuring device allowed students to calculate the density and molar mass of air, based on the dependence of altitude pressure. The peculiarities of pressure registration using the PhyPhox application determined the methodology for performing measurements and calculating errors. Processing the results of the experiment stimulated a more detailed familiarization of students with the calculation of mean value and random errors using MS Excel, Google Spreadsheets, or other mathematical packages for this purpose. The values of density and molar mass of air obtained by students generally agree well with the tabulated data.

Modern smartphones, tablets, and smartwatches are advisable for conducting physical experiments by students during both remote and classroom learning. However, when formulating the task, you need to take into account the availability of the required sensor in the smartphone. For example, a pressure sensor is built into the iPhone, high-priced Samsung models, and smartwatches.

The prospects for further investigations we see in the formulation of tasks for physical experiments that can be conducted at home using affordable and home-made equipment, as well as smart devices.

REFERENCES

1. Bug-Os, M.A.A.C., Marte, S.J., & Pili, U.B. (2023). Verification experiment of the coefficient of static and kinetic friction utilizing a mobile application. *Physics Education*, 58 (6), 065013. https://doi.org/10.1088/1361-6552/acf431
2. Colt, M., Popescu, M., & Dragomir, F. L. (2021). Current Experimental Methods in Physics Using the Smartphone Sensors. *The 16th International Conference on Virtual Learning VIRTUAL LEARNING – VIRTUAL REALITY*, 223-232. https://icvl.eu/documents/9/ICVL2021-Proceedings-SITE.pdf#page=223
3. Csernovszky, Z., Hömöstrei M., & Kurucz, K. (2024). Study of damped oscillations using Phyphox and Arduino controlled Hall-sensor. *Journal of Physics: Conference Series*, 2693 (1), 012004. https://doi.org/10.1088/1742-6596/2693/1/012004.
4. Cukierman, U. R., Silvestri, S., Drangosch, J., Ferrando, D. P., Agüero, M., Delmonte, R., Corrao, L. G., & Saclier, L. (2017). Bridging the gap between first-year students and Engineering: A novel application of mobile technologies for improving Mathematics and Physics learning. *Conference: 2017 7th World Engineering Education Forum (WEEF)*, 834-838. https://www.researchgate.net/publication/327820916_Bridging_the_gap_between_first-year_students_and_Engineering_A_novel_application_of_mobile_technologies_for_improving_Mathematics_and_Physics_learning.
5. Holovina, N. A., Kobel, H. P., Doskoch, V. P., & Kalapusha, L. R. (2013). *Laboratornyi praktykum iz molekuliarnoi fizyky y termodynamiky [Laboratory workshop on molecular physics and thermodynamics.]*. Lutsk : VezhaDruk, 91-95. https://evnuir.vnu.edu.ua/bitstream/123456789/5219/1/Laboratornyy%20praktykum.pdf (in Ukrainian).
6. Imtinan, N., & Kuswanto, H. (2023). The Use of Phyphox Application in Physics Experiments: A Literature Review. *JIPF (JURNAL ILMU PENDIDIKAN FISIKA)*. 8(2), 183-191. https://doi.org/10.26737/jipf.v8i2.4167
7. Klein, P., Ivanjek, L., Dahlkemper, M. N., Jeličić, K., Geyer, A., Küchemann, S., & Susac, A. (2021). Studying physics during the COVID-19 pandemic: Student assessments of learning achievement, perceived effectiveness of online recitations, and online laboratories. *PHYSICAL REVIEW PHYSICS EDUCATION RESEARCH 17, 010117*. https://doi.org/10.1103/PhysRevPhysEducRes.17.010117
8. Kuhn, J., & Vogt, P. (2022). Experiments with mobile devices — A retrospective on 10 years of iPhysicsLabs. *The Physics Teacher* 60, 88–89. https://doi.org/10.1119/10.0009416
9. Lincoln, J. (2024). Biot–Savart law with a smartphone: Phyphox app. *Phys. Teach*. 62, 72–73. https://doi.org/10.1119/5.0188271
10. Milner-Bolotin, M., & Milner, V. (2023). Breaking the vicious circle of secondary science education with twenty-first-century technology: Smartphone physics labs. *Challenges in Science Education: Global Perspectives for the Future*, 177 – 199. https://doi.org/10.1007/978-3-031-18092-7_9
11. Podlasov, S., Sverdlichenko, D., & Matviichuk, O.(2023). Eksperymentalni zadachi z fizyky v tekhnichnomu universyteti [The experimental physics problems at the technical university]. *Fizyko-matematychna osvita –Physical and Mathematical Education*, 38(3), 50-56. https://doi.org/10.31110/2413-1571-2023-038-3-007 (in Ukrainian).
12. Ruda, L. M. (2018). *Laboratornyi praktykum z fizyky: mekhanika ta molekuliarna fizyky [Laboratory workshop on physics: mechanics and molecular physics]*. Kharkiv. 34-38. http://lib.kart.edu.ua/handle/123456789/1385 (in Ukrainian).
13. Slipukhina, I., Chernetckiy, I., Kurylenko, N., Mieniailov, S., & Podlasov, S. (2020). Applied Aspects of Instrumental Digital Didactics: M-learning with the Use of Smartphone Sensors. *ICTERI 2020 ICT in Education, Research and Industrial Applications. Integration, Harmonization and Knowledge Transfer. Proceedings of the 16th International Conference on ICT in Education, Research and Industrial Applications. Integration, Harmonization and Knowledge Transfer. Volume I: Main Conference Kharkiv, Ukraine, October 06-10*. http://ceur-ws.org/Vol-2740/20200173.pdf (in English)

14. Sukariasih, L., Erniwati, La Sahara, Hariroh, L., & Fayanto, S. (2019). Studies the use of smartphone sensor for physics learning. *International journal of scientific & technology research*, 8, 10. https://www.ijstr.org/final-print/oct2019/Studies-The-Use-Of-Smartphone-Sensor-For-Physics-Learning.pdf.
15. Sárközi, Z., & Vörös, A.-I.-V. (2023). A version of Buys Ballot experiment for quantitative proof of the Doppler effect in students' laboratory work, adapted to online conditions. *AIP Conference Proceedings*, 2843 (1), 050013. https://doi.org/10.1063/5.0150800
16. Wye, S. (2023). Teaching remote laboratories using smart phone sensors: determining the density of air. *Phys. Educ. 58 015002*. https://iopscience.iop.org/article/10.1088/1361-6552/ac9816.
17. Zhuang, W., Cao, H., Zhang, Z., Zhang, J., Zhao, X., Zhang, Y. (2023). Two capacitors' experiments using Phyphox app and ESP32 development board. *Physics Education*, 58 (5), 055013. https://doi.org/10.1088/1361-6552/ace57e

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