

## Investigation of instructional practices in high-school atomic and subatomic physics

K. Ilchev\*, I. Kotseva

*Sofia University „St. Kliment Ohridski”, Faculty of Physics, Sofia, Bulgaria*

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Education research has illuminated numerous student misconceptions of atomic and subatomic physics. Furthermore, there is evidence that high-school students' engagement is positively correlated with an increase in the variety of applied teaching methods. In this paper, we systematically investigate proposed methods which are likely to improve high-school students' understanding of the microscopic world. This includes specific application of models, cooperative learning, problem-based learning and others. We comment on trends and empirical evaluation within the diverse assortment of proposed activities.

**Keywords:** physics education, secondary education, instructional practices, atomic physics, nuclear physics, particle physics

### INTRODUCTION

Physics at the high-school level covers many conceptually difficult ideas, especially when dealing with phenomena of the microscopic domain. Principles may counter previous student conceptions. Moreover, events are generally not directly visible. Students must develop an adequate model in their mind and relate it to the governing laws of nature.

Several papers document and analyse common high-school student misconceptions in the area of atomic, nuclear and particle physics. For example, Tuzón and Solbes [1] report that while some students have heard about terms such as particle accelerators or the Higgs boson, they still confuse modern with classical physics ideas. The authors empirically show that students may not distinguish the fundamental forces, e.g., when identifying the force responsible for keeping the electron bound to the nucleus. Other reported difficulties relate to the question of how repelling protons can form stable nuclei and which kind of interactions occur when nuclei transform. Another conclusion is that students confuse the hierarchy of microscopic constituents, for instance claiming that nuclei are composed of atoms, etc. These findings point towards the need of instructional practices which establish systematic knowledge and thereby allow students to correctly identify and contextualise scales and fundamental forces.

Another set of misconceptions relates to the atomic and radiation models. Savall-Alemany *et al.* [2] report a multitude of specific difficulties associated with atomic spectra and their interpretation. Students may not account for the quantization of energy levels, grasp photons as being

always absorbed by the atom, confuse the ground state energy, falsely relate high photon intensity with high frequency. Other misconceptions relate to atomic processes where students have claimed that transitions to lower states are always transitions to the ground state, etc. Some statements show that students do not apply energy conservation in the matter-radiation interaction. The authors suggest providing students with more opportunities to use models in order to explain various emission and absorption processes.

When teaching high-school nuclear physics, one will likely encounter student's fear of radiation or "radiophobia" (Tsuruta *et al.* [3]), probably induced by modern media or past historic events. A lack of knowledge makes it harder for students to grasp radioactivity benefits for society alongside interdisciplinary connections, e.g., to geology, chemistry and biology (de Cicco *et al.* [4]). In addition, teachers may find that experimental activities are not readily available (Bastos *et al.* [5]), either due to the high cost of radiation sources/detectors or safety regulations. Which kind of activities could help students explore the hazards/advantages of radiation, alongside the connection to technology, politics and ethics (Schibuk [6])?

Recently, STEM education has gained popularity in research. It aims to prepare students for real, complex problems by increasing their activity in the classroom. The idea is to deepen student thinking, thereby guiding them towards higher cognitive levels. One question of interest is whether a variety of applied teaching methods helps students tackle more difficult problems.

\* To whom all correspondence should be sent:  
E-mail: konstantin.ilchev@hotmail.com

A statistical correlation of this type has been found within data from TIMSS Advanced 2015. This international study provides results from physics tests and student/teacher questionnaires. It encompasses nine countries and deals with students in their final year of secondary education (ISCED 3). The test consists of three content domains and three cognitive domains - "Knowing", "Applying" and "Reasoning" (Mullis and Martin [7]). It is possible to analyse TIMSS Advanced data with a web-based data analysis tool called IDE (<https://nces.ed.gov/surveys/international/ide/>). This has allowed us to check the following hypothesis: "A variety of applied teaching methods is positively correlated with student results from the "Reasoning" section of the physics test". IDE has a built-in significance test which confirmed the hypothesis, with  $p < 0,05$ . (International average; Scale: reasoning (2015); Variable: [PS3BP18M]. For further details, contact the leading author.)

Analysis of TIMSS data has also shown a positive correlation between the variety of teaching methods and minutes spent per week on physics outside of class (which may relate to student motivation).

### Research Questions

In view of the aforementioned empirical findings, we formulate the following questions:

- RQ1) Which **instructional activities** are suggested in atomic and subatomic high-school physics articles?
- RQ2) Which kind of **student involvement** is described in these articles?
- RQ3) Which instructional practices have (empirically) shown to be "**effective**"?

### Method of Research

We chose to browse the databases *Scopus*, *ERIC* (and *Google Scholar*) for articles related to questions RQ1-3. This section summarizes the steps which led to a set of 32 included articles. The first step was to specify how papers are going to be filtered. We achieved this by applying the following **search string** to all three databases:

("secondary education" OR "high schools")  
AND (instruction OR teaching)  
AND (atom\* OR nuclear OR particle)

We also checked for recent reviews which are related to our investigation and decided to exclude the term "quantum" from our search string. The main reason is that such a review has already been published. Krijtenburg-Lewerissa *et al.* [8] included 74 articles (including secondary education) and looked into quantum mechanics misconceptions and

teaching strategies, among other things. The authors conclude that a variety of instructional practices are proposed but there is too little empirical evidence for the effect of these strategies.

Scopus returned 312 hits while ERIC yielded 364 articles. We focused our search by applying the following inclusion criteria: Documents must:

- C1) .be accessible in English;
- C2) .be articles or reviews;
- C3) .be published after 2002;
  
- C4) .focus on activities for high-school students;
- C5) .provide a description of a practice or student involvement;
- C6) encompass at least one atomic, nuclear or particle physics topic and cannot be limited to teaching quantum physics.

Criteria 1-3 were easily applied because both Scopus and ERIC allow for filtering by language, publication date and document type. This was done first. Scopus yielded **33 hits** (after limiting articles to "Physics and Astronomy") while ERIC returned **53 hits** (after limiting to "Physics").

Criteria 4-6, however, required looking into the abstract (and usually – the whole text) of the remaining articles. Criterion 4 ensures that the article relates to secondary education. This excludes articles covering undergraduate/pre-service teachers' education. Criterion 5 excludes articles dealing either with changes to the curriculum or strategies centred around the teacher explaining specific concepts. Criterion 6 excludes most but not all quantum-related articles as some of these naturally have useful intersections with atomic and subatomic physics. Specifically, some excluded articles focused on topics such as chemical kinetics, bonding; electric/magnetic fields; dark matter, cosmic expansion and other astrophysical concepts without direct relation to particles; special theory of relativity concepts; particle erosion; thermodynamics topics such as the behaviour and motion of particles in gases/liquids/solids. Further details about excluded articles can be provided by the leading author.

We are finally left with 10 (+2 extra) = 12 Scopus articles and 16 documents from ERIC. We included 4 additional articles from Google Scholar, which sums up to **32 articles to be analysed**.

Note that the 2 extra articles from Scopus were identified during a previous search including the "quantum" keyword. We decided to keep them because one is related to an experimental activity (photoelectric effect) and the other deals with a very interesting inquiry activity (nanotechnology). We also included 4 articles from G. Scholar, which does

add selection bias. Given our research questions, however, we decided to include the papers because they either give further variety in proposed student activities or provide additional empirical evidence. The included articles can be found in Table 1 of the following section.

## RESULTS AND DISCUSSION

Once the 32 articles were selected, we employed the following strategy during our analysis: papers were carefully examined for instructional activities/setup, empirical evaluation and specific student involvement. By “student involvement” we mean distinct activities students may participate in. While one option is to classify instructional practices as being either model-based, problem-based, design-based, etc., we chose to apply an idea elucidated by Geis [9]. The author suggests that rather than categorizing activities according to utilized methods such as “lecture” or “computer-based”, one may want to pursue the “critical features” of a given activity – attributes which lead to success and may be shared between various methods. The features “connections to daily life” or “receiving feedback”, for example, may or may not be included in a lecture, problem-based learning, cooperative learning, etc.

We chose to consider 17 distinct actions students may become involved in during activities. These were adapted from the TIMSS Advanced 2015 and 2019 questionnaires. We also checked whether a given article describes a procedure or “TLS” (teaching-learning sequence) and whether it includes a quantitative evaluation of the activity. We give more information on the type of empirical evidence provided (see Appendix).

The results of our investigation are summarized in Table 1. It is color-coded and ordered by topic (atomic, nuclear, particle physics, combined/related articles). Note that spotting a feature in a given article (marked with an “X” in the table) means that it is either explicitly mentioned or (in our opinion) implied by the authors.

The purpose of Table 1 is twofold. Teachers and researchers can browse recent articles very quickly based on specific actions students get involved in. For example, one may be interested in nuclear physics group activities or experiment ideas. We do not suggest comparing articles (i.e., table rows) because some documents are naturally longer than others. They may describe long-term projects which involve students in various ways. On the other hand, some articles focus only on specific aspects of an activity, thereby providing very detailed information. Another way to use the table, however, is to compare table columns.

Table 2 shows the frequency of features across all documents. While it may include some bias as mentioned above, it still portrays current trends. As can be seen from Table 2, most articles describe a procedure. Also, most presented activities encourage students to link atomic and subatomic physics ideas to previous content knowledge and to aspects of everyday life. A sizable fraction of papers (63%) focuses on group work and ways of presenting information (66%). More than half (59%) of the papers mention feedback to students. Interestingly, 11 of the papers do not include the use of computers. Despite the modern trend of using simulations, many articles illustrate actual hands-on procedures which deal with or visualize microscopic phenomena in other ways. Moreover, computer use is not central in some of the other papers. 50% of articles refer to experimental procedures while 31% cover experimental design/constructing devices in a real laboratory setting. Less than half of the articles describe classroom discussions, explaining answers and expressing ideas. The lowest percentages are appointed to field work (which is understandable as these are usually long-term activities or international projects) and quantitative evaluations. Another way to concisely present suggested practices is to categorize them (see Table 3).

## CONCLUSION

Scopus, ERIC and Google scholar returned articles which cover a variety of instructional activities (Table 3). They allow us to identify and quickly locate specific student involvement (Table 1) and form tendencies (Table 2). The methods presented by the authors generally aim to tackle student misconceptions or relate the topic to student lives. Several papers put an emphasis on scientific literacy, ethics and society. Articles provide creative ideas for constructing and using devices in the classroom, games involving the whole class, working with scientific texts, inquiry-based assignments, university and international collaboration, as well as participation in real, long-term scientific projects. Only some of the practices require computers. Articles generally describe an instructional sequence but rarely (less than 25%) provide quantitative evidence. Authors assess student learning achievement, self-efficacy, conceptions of learning, scientific literacy, attitude and identify misconceptions. The effects reported in articles are mainly positive (see Appendix for details).

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**Table 1.** Features of included articles

Article (year)/description	Quant. eval. ?	Descr. procedures /"TLS"	Class-room disc.	Daily lives	Link knowl.	Expl. answers	Express ideas	Group Work	Com-puter use	Plan exp./construct.	Conduct exp.	Inter-pret data	Present data	Observe phenom.	Use evidence to supp.	Watch demo. of exp.	Field work	Chall-enging exs.	Give feed-back
<b>ATOMIC:</b>																			
Savall-Alem any, F. et al. (2019) PBL atomic spectr.	Y	Y	X	X	X	X	X	X		X	X	X		X	X	X			X
Rodriguez, L. V. et al. (2020) Inquiry quantum.	Y	Y	X	X	X	X	X	X	X			X	X	X	X	X			X
Kontomaris, S. V. et al. (2020) Ionizing vs. non-ion. rad.	N	N		X	X														
Cziprok, C. et al. (2016) Vee heuristic, photoel. eff.	N	Y		X	X			X	X		X	X	X		X				
Cai, S. et al. (2020) AR, photoel. eff.	Y	Y						X	X		X	X		X					X
Woo, Y. et al. (2019) Constr. spectrometer	N	N							X	X			X						
Maffei, G. et al. (2011) Mosaic method, atom. spectra	N	Y	X		X	X		X				X	X	X	X				X
Salazar, R. et al. (2019) Modeling activities	Y	Y	X	X	X	X	X	X	X				X						X
<b>NUCLEAR:</b>																			
Bastos, R. O. et al. (2016) Experiments, low-cost.	N	N		X							X	X							X
Tsuruta, T. et al. (2009) Exp., track detection	N	N		X								X		X		X	X		
De Cicco, F. et al. (2017) Radon exp., School-uni collab.	N	Y		X	X	X		X	X	X	X	X	X	X	X		X	X	X
Schibuk, E. (2015) Activities (Manhattan project)	N	Y	X	X	X	X	X	X	X										X
Sengdala, P. et al. (2014) NOS teaching, Nucl./peace.	N	Y	X	X	X	X	X	X					X						X
Shastri, A. (2007) Constr. Slide-rule comp., nuclear eff.	N	Y	X	X	X	X	X		X	X		X	X		X			X	
Brown, T. (2014) Exp., radioactive dating	N	Y		X	X				X		X	X		X					X
Kapon, S. (2013) Scientific text for students (Einst. $E=mc^2$ )	N	Y	X	X	X	X	X	X							X			X	X
KRIŠŤÁK, L. et al. (2013) Multimedia/DVD activity	Y	Y	X	X	X	X		X	X		X	X			X	X			X
Elbanowska-Ciemuchowska, S. et al. (2011) Many activities	N	Y	X	X	X		X	X	X		X	X	X		X		X	X	X

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Article/ activity	Quant. eval. ?	Descr. procedures /"TLS"	Class-room disc.	Daily lives	Link knowl.	Expl. answers	Express ideas	Group Work	Computer use	Plan exp./ construct.	Conduct exp.	Interpret data	Present data	Observe phenom.	Use evidence to supp.	Watch demo. of exp.	Field work	Challenging exs.	Give feedback
<b>PARTICLE:</b>																			
Schramek, A. et al. (2019) <u>Research-based teaching, Uni-school. Detectors</u>	N	Y		X	X	X	X	X		X	X	X	X		X	X	X	X	X
Bressan, E. (2011) <u>Research-based teaching, Uni-school, CR detection</u>	N	Y		X					X	X	X	X	X		X		X	X	X
Bardeen, M. et al. (2018) <u>Online tools, QuarkNet</u>	Y	Y	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X
van den Berg, E. et al. (2006) <u>Fast feedback, symmetries etc.</u>	N	Y	X		X	X		X										X	X
Kourkoumelis, C. et al. (2014) <u>Online tool, HYPATIA</u>	N	Y	X		X				X			X	X	X	X			X	X
Goldader, J. D. et al. (2010) <u>Constr. cheap CR detec.</u>	N	N							X	X	X		X					X	
Brouwer, W. et al. (2009) <u>Research-based. ALTA proj.</u>	N	Y		X	X	X	X	X	X		X	X	X		X		X	X	
de Souza, V. et al. (2013) (re-) <u>Constr. CR Impact point</u>	N	Y			X					X		X	X		X			X	X
Badalá, A. et al. (2007) <u>Data analysis, Simul. CR data</u>	N	Y	X		X			X	X			X	X					X	
<b>COMBINED /OTHER:</b>																			
Bussani, A. (2020) <u>Dice game, microsc. sys.</u>	N	Y	X		X			X	X			X			X			X	
Kvita, J. et al. (2018) <u>Particle camera for exp.</u>	N	Y		X	X				X		X	X	X	X		X	X	X	
Keegans, J. D. et al. (2021), <u>Outreach, Python, Nucleosynth.</u>	Y	Y			X			X	X			X	X		X			X	X
Planinšič, G. et al. (2008), <u>Constr. AF microscope model, Nano.</u>	N	Y		X	X			X		X	X	X	X		X	X		X	
Laubach, T. A. et al. (2010), <u>Quided inquiry, Nano.</u>	N	Y		X	X	X			X		X	X	X		X			X	

**Table 2.** Trends

Frequency (out of 32 papers)	Variable		Frequency (out of 32 papers)
Describe procedures/ "TLS"	84%	Conduct experiment	50%
Link knowledge	81%	Classroom discussion Explain answers	47%
Interpret data	75%	Express ideas	34%
Daily lives	69%	Plan experiment/ construct something Observe phenomenon	31%
Present data, Computer Use	66%	Watch demonstration of an experiment	25%
Group work	63%	Quantitative evaluation Field work	22%
Challenging exercises Give feedback Use evidence to support	59%		

**Table 3.** Summary of proposed activities

<p><b>Educational games</b> Duhdonium, competitive dice game. Microscopic systems. Bussani, A. (2020)</p> <p><b>Specific instructional methods</b> Fast feedback method. Particle physics. van den Berg, E. <i>et al.</i> (2006) Modelling method. Atomic models. Salazar, R. <i>et al.</i> (2019) Mosaic (Jigsaw). Atomic spectra. Maftei, G. <i>et al.</i> (2011) Focus on analogies. Ionizing vs. non-ionizing radiation. Kontomaris, S. V. <i>et al.</i> (2020) Guided problem-based learning. Atomic spectra. Savall-Aleman, F. <i>et al.</i> (2019) Many different methods. Nuclear physics. Elbanowska-Ciemuchowska, S. <i>et al.</i> (2011) Reading a scientific text. Class discussions. Einstein's paper on <math>E=mc^2</math>. Kapon, S. (2013) Reading articles. NOS teaching. Nuclear physics and peace. Sengdala, P. <i>et al.</i> (2014) Flipped classroom approach. Discussions. Studying the Manhattan project. Schibuk, E. (2015)</p> <p><b>Experiments</b> =&gt; <b>Conduct</b> 4 mystery vials with nano-solutions. Inquiry. Laubach, T. A. <i>et al.</i> (2010) Particle camera MX-10: Particle and nuclear physics. Kvita, J. <i>et al.</i> (2018) Photoelectric effect, using the Vee heuristic. Cziprok, C. <i>et al.</i> (2016) Radioactive dating in the classroom, using Cobalt-60. Brown, T. (2014) Nuclear track detection methods. Tsuruta, T. <i>et al.</i> (2009) Nuclear experiments with low-cost instruments. Nuclear physics. Bastos, R. O. <i>et al.</i> (2016)</p> <p>=&gt; <b>Plan/construct</b> Constructing an atomic force microscope model. Planinšič, G. <i>et al.</i> (2008) Reconstruction of impact point and arrival direction of a CR particle. de Souza, V. <i>et al.</i> (2013) Constructing a cheap cosmic ray detector. Goldader, J. D. <i>et al.</i> (2010) Constructing detectors at a research center. Research-based teaching. Schramek, A. <i>et al.</i> (2019) Constructing a high-res 3D-printed smartphone spectrometer. Atomic. Woo, Y. <i>et al.</i> (2019) Constructing a slide-rule computer. Effects of nuclear weapons. Shastri, A. (2007)</p> <p>=&gt; <b>Data analysis</b> Extensive air showers of particles. Particle physics. Badalà, A. <i>et al.</i> (2007)</p> <p><b>Online tools/applets/multimedia</b> HYPATIA. (ATLAS event data). Particle physics. Kourkoumelis, C. <i>et al.</i> (2014) Go-Lab activities. Photoelectric effect sequence. Rodriguez, L. V. <i>et al.</i> (2020) Multimedia DVD - nuclear physics. KRÍŠŤÁK, L. <i>et al.</i> (2013)</p> <p><b>Augmented reality (AR)</b> Photoelectric effect experiment using AR in groups. Cai, S. <i>et al.</i> (2020)</p> <p><b>Outreach/Research program</b> ALTA study of cosmic ray bursts. Hypotheses in student projects. Brouwer, W. <i>et al.</i> (2009) QuarkNet education program. Research, masterclasses, e-Labs. Bardeen, M. <i>et al.</i> (2018) EEE (Extreme Energy Events) project: Cosmic ray detectors at schools. Bressan, E. (2011) ENVIRAD - Radon measurements at schools and university. De Cicco, F. <i>et al.</i> (2017) ThaiPASS - Data analysis using Python. Astroparticle physics. Keegans, J. D. <i>et al.</i> (2021)</p>
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**APPENDIX: OVERVIEW OF EMPIRICAL EVALUATION**

Article (Year)	Context of study/sample	Control group	Pre-test	Post-test	Statistical analysis	Results
Savali-Alemany, F. et al. (2019) PBL atomic spectr.	Assess learning achievement and identify student misconceptions. Experimental group (PBL): total of 74 students, 2 high schools. Control group (lectures+problem solving): total of 67 students. Teachers – over 10 year experience, incl. PBL.	Yes	Yes. No correct answers - exp. Or ctrl. group.	Yes. Included in appendix. Open-ended answers to three questions. Classification of student answers. High inter-rater reliability. 5 students who performed very well additionally interviewed to check knowledge.	Yes. Chi-square test. Fisher's p. Cohen's h.	Experimental group performed stat. signif. better in all 3 questions. Cohen's h suggests a large effect size. Discussion of observed student misconceptions.
Rodriguez, L. V. et al. (2020) Inquiry quantum.	Assess learning outcomes and identify student misconceptions. 114 students from four high schools.	No	No	Data collection through digital environment. MCQ and open-ended questions.	Correct answers reported as a %.	Majority of students understand critical concepts related to the photoelectric effect. Less successful in answering certain open-ended questions.
Cal S. et al. (2020) Augmented reality, photoel. eff.	Assess student self-efficacy and conceptions of learning. Experimental group (AR): total of 49 students. Control group (flash-based): total of 49 students from one high school.	Yes	Yes. No significant difference.	Yes. SEOLP questionnaire, COLP questionnaire.	Yes. t-test analysis. ANCOVA.	AR group achieved significantly higher scores on physics learning self-efficacy compared to the Flash group. (4 out of 6 aspects showed improvement, namely conceptual understanding, higher-order thinking skills, practical work and social communication.) AR group scored higher in applying, understanding and seeing in a new way. (higher-level conception) They scored lower in memorizing and calculating (lower-level conception).
Salazar, R. et al. (2019) Modeling activities	Assess learning outcomes (Hake's gain score). 20 students from one school.	No	Yes	Yes. Included in appendix.	Yes. Hake's normalized gain.	Most answers show a high conceptual gain (g>0.7). Only three questions still trouble students (g<0.3). Average gain for the 20 questions is high (g=0.72). Authors report student answers to activities.
KRIŠTÁK, L. et al. (2013) Multimedia/DVD activity	Assess learning gains in area of: remembering, understanding, transfer of specific and non-specific knowledge (analysis, synthesis etc.). Experimental group (Multimedia DVD): 104 students. Control group ("traditional" teaching): 101 students. Students are from four high schools. Same teacher taught the students (for each school).	Yes	No	Yes. Included in appendix. Open-ended/MCQ.	Yes. F-test and t-test. Normal distribution verified for both groups.	Students using DVD multimedia scored significantly higher than students using "traditional" methods, in all three categories: specific and non-specific transfer, remembering and understanding.
Bardeen, M. et al. (2018) Online tools, QuarkNet	Assess increase in scientific literacy of students. Masterclass effectiveness - knowledge and attitude. 582 students.	No	Yes. Conceptual maps. Masterclass: Yes. Masterclass: Yes.	Yes. Conceptual maps. Masterclass: Yes.	Yes. However, analysis of effect sizes and differences only mentioned; no details included in paper.	Post-maps show a more sophisticated or scientifically literate understanding of the scientific process. Improvements for students with higher and with lower pre-program maps. Masterclasses: Positive attitude towards physics: 4.0 average out of 5. Increase student knowledge and skills.
Keegans, J. D. et al. (2021), Outreach, Python, Nucleosynthesis	Assess student attitude and skills. 60 students from 30 schools	No	No (2018 event). Yes (2019 event).	Yes. Questionnaire included in appendix.	No, however all student responses clearly shown on histogram.	(2018) Largely positive attitude towards the summer school. (2019) Self-assessment shows that students believe their programming and computer science skills have increased. Most students would pursue a STEM career. Perceived usefulness of Python, interest in nuclear astrophysics and STEM-career interest have increased (pre- to post-test).