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Introducing 12 year-olds to elementary particles

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Abstract
We present a new learning unit, which introduces 12 year-olds to the subatomic structure of matter. The learning unit was iteratively developed as a design-based research project using the technique of probing acceptance. We give a brief overview of the unit's final version, discuss its key ideas and main concepts, and conclude by highlighting the main implications of our research, which we consider to be most promising for use in the physics classroom.

1. Introduction

Integrating modern physics into the curriculum is a question that has recently received ever increasing attention. This is especially true since in most countries the topic of modern physics is usually added at the end of physics education—if at all [1]. However, since these chapters—and here especially the Standard Model of particle physics—are considered to be the fundamental basics of physics, this situation might hinder the development of coherent knowledge structures in the physics classroom. Hence, one is faced with the question of whether it makes sense to introduce elementary particle physics early in physics education. Therefore, to investigate this research question, we have developed a learning unit, which aims to introduce 12 year-olds to elementary particles and fundamental interactions [2].

The learning unit consists of two consecutive chapters. It starts with an accurate description of the subatomic structure of matter by showcasing an atomic model from electrons to quarks. This first chapter is followed by the introduction of fundamental interactions, which on the one hand complete the discussion of the atomic model, and on the other hand set up possible links to other physics phenomena. An integral component of the learning unit is its independence from the physics curriculum and students' prior knowledge about particle physics. Indeed, since every physics process can be traced back to fundamental interactions between elementary particles, the use of the learning unit is not restricted to a certain age-group. Ideally, it can even be used at the beginning of physics education to enable an early introduction of key terms and principal concepts of particle physics in the classroom.

Following the framework of constructivism [3], the initial version of the learning unit was based on documented students' conceptions. Taking these into account enabled us to avoid potential difficulties for students, which might occur due to inadequate information input. As a next step, the initial version was developed by means of a design-based research [4] project with frequent adaptions of the learning unit. Here, we used the technique of probing acceptance [5] to conduct one-on-one interviews with 12 year-olds to evaluate the material developed. Based on the students' feedback, the learning unit was iteratively modified and evaluated until we arrived at the final version [2].

In this article, we give an overview of documented students' conceptions, which were relevant to the development of our learning unit. Next, we present the key ideas and main concepts of the learning unit by discussing its first chapter, which introduces the subatomic structure of matter. We then summarise the results from our development of the learning unit before concluding with a brief summary of suggestions, deduced from our research results, which we consider to be adequate and promising for use in the classroom.

2. State of research

When it comes to students' conceptions about the atomic model of matter, one finds initial studies, conducted in chemistry education research in the 1980s. Here, it was already shown that middle and high school students use particle models mainly to describe the nature of gases, but do not consider it to be their first choice when discussing everyday physics phenomena [6–8]. However, if a suitable particle model is offered as a meaningful alternative, most students accept and use it [9, 10]. In addition, when looking at various age groups, one finds that high school students tend to accept particle models more easily compared to middle school students [6, 11]. However, concerning the understanding of the atomic model, the same misconceptions can be documented in both age groups [7, 12].

Since everyday life suggests a continuous rather than particular nature of matter—after all, ordinary matter usually appears to be compact and not at all corpuscular—it does not come as a surprise that students tend to prefer a continuous description of matter [6, 12–15]. Moreover, after introducing a particle model in the classroom, a mixing of both conceptions can be documented. This can be interpreted as the attempt of students to integrate the novel particle model into their existing continuous conception of matter [6, 12, 13]. The development of such inadequate conceptions can even be supported by erroneous textbook illustrations. For instance, this is the case in the infamous illustration of a glass of water, which shows H_2O-molecules floating around in water [13].

Last, even if middle and high school students accept a particle model, this neither includes the notion of the constant motion of particles nor the idea of empty space. These two concepts are both only rarely documented with students, which instead leads to persistent misconceptions [7, 11, 13]. In addition, students also tend to anthropomorphise particles by imbuing them with everyday characteristics, such as colours and faces [12, 13, 15].

3. Learning unit

As mentioned above, our learning unit on the subatomic structure of matter was developed based on documented students' conceptions. The rationale of the unit is to enable 12 year-olds to construct knowledge on their own. Here, we encountered challenges due to the abstract nature of particle physics, which hinders the development of a correct and adequate learning unit. However, we found that by constantly putting the focus of the unit's content on the model aspect of physics, the abstractness of elementary particles can be incorporated in a meaningful way. In addition, to avoid triggering potential misconceptions, we also focused on linguistic accuracy when formulating the contents of the learning unit. Third, since education research has identified erroneous graphical representations as a main source for students' misconceptions, the learning unit is supported by the use of novel typographic illustrations. All told, the following three concepts are fundamental to the design of the learning unit:

- Model aspect of particle physics
- Linguistic accuracy
- Typographic illustrations

To illustrate the essential character of these three main concepts, we now give a brief overview of the learning unit's first chapter, which introduces the subatomic structure of matter. The aim of this first chapter is to outline an adequate atomic model, which mentions Democritus as the originator of the idea of atoms, but otherwise focuses on a modern description of atoms. Hence, it incorporates electrons and quarks as elementary particles, while protons and neutrons are introduced as particle systems, which are made of particles. Since gluons are only introduced in the unit's second chapter, which focuses on fundamental interactions, they are omitted at this early stage. However, through the careful use of colours for the typographic illustrations, the introduction of colour charge is already set up to be introduced in the second chapter. Furthermore, the unit's first chapter is based on the following ten key ideas, which are fundamental to the introduction of the subatomic structure of matter:

1. Matter is everything that can be touched, practically or theoretically.
2. Reality is described through models. For example the model of particle physics.
3. In the model of particle physics, there are atoms, which may combine to form compounds.
4. In this model, atoms are divided into two areas: the nucleus-space and the orbital-space.
5. In the nucleus-space, protons and neutrons are located.
6. Protons and neutrons are particle systems, which are made of quarks.
7. Quarks are indivisible. In this model, these are called elementary particles.
8. In the orbital-space, it is likely to find electrons.
9. Electrons are indivisible. In this model, these are called elementary particles.
10. In this model, apart from particles, there is only empty space.

These key ideas were reconstructed together with education researchers and teachers, and iteratively modified and refined based on the students' evaluations during the one-on-one interviews. This led to the final version, which was validated by particle physicists and proved itself to be adequate and well-suited to introduce the subatomic structure of matter to grade-6 students [2]. However, our results also indicate that students only find it easy to accept and use these key ideas if the main concepts of the learning unit are also taken into account. Indeed, focusing on the model aspect of physics and on linguistic accuracy is prominently reflected in the phrasing of the ten key ideas and our findings show that they are essential for the successful implementation of the learning unit. The same goes for the typographic illustrations, which accompany the learning unit. Therefore, we give a brief overview of the three main concepts to highlight their importance for the unit's design.

3.1. Model aspect of particle physics

One of the biggest challenges when it comes to teaching particle physics is its abstractness. Hence, it does not come as a surprise that this topic is only rarely introduced in the physics classroom. After all, explanatory hands-on experiments are limited, physically precise explanations are hardly adequate for high-school level, and, due to the inconceivable dimensions involved, graphical representations fail to convey a realistic image. However, this allows the model aspect of particle physics to stand out. Indeed, the learning unit strongly focuses on conveying the idea that the use of models is essential in science, particularly in particle physics. The rationale of this approach is to highlight the key process of model-building, since it is argued that thinking in and with models is an essential component of appropriate science knowledge [16, 17]. Specifically, the phrasing 'With this model, we describe…' plays a big role and is being used frequently throughout the unit's key ideas and key phrasings. Instead of the Standard Model of particle physics, however, we use a simplification and introduce 'the model of particle physics'. During first iterations of the learning unit, this modification proved itself to be very successful, since students showed difficulties with the term 'Standard Model'. Hence, the original term was omitted and replaced by its simplified version, which appealed greatly to all students during further evaluations. This example leads to the discussion of the second main concept, linguistic accuracy, which played a significant role in the development of the learning unit as well.

3.2. Linguistic accuracy

Another challenge in particle physics is how best to talk about particles and atoms in general. Since in the classroom one needs to jump back and forth between technical jargon and everyday language [18], this is especially problematic in the case of inconceivable particles. Hence, to prepare a meaningful learning unit, careful definitions of key terms and the rephrasing or avoidance of misleading terms are required. Indeed, the rapid pace of discovery in the early days of particle physics led to the establishment of key terms, which now convey an outdated description of modern particle physics, and should therefore be avoided in the classroom. Here, the so-called 'particle zoo', which was used to describe the dozens of newly discovered 'elementary particles' is a prominent example. This unfortunate term originates from a time when, in the absence of a complete quark theory, each newly discovered combination of quarks was classified as an elementary particle. Nowadays, following the modern description of only leptons and quarks as elementary particles, the notion of a 'particle zoo' can be seen as anachronistic and thus detrimental to students' understanding.

Hence, we consider linguistic accuracy to be a very important aspect of the learning unit. Indeed, at the beginning of the development of our learning unit, we identified several terms and phrasings, which students evaluated to be difficult to understand. However, we also found that, by making minor adjustments to these terms and phrasings, or by rephrasing them, students showed broad acceptance. For instance, instead of using the 'nucleus', the learning unit introduces the 'nucleus-space'. This was prompted by a common conception, which we found early in our research. Students frequently stated that protons and neutrons were embedded in the nucleus and were confused when asked to explain what this nucleus might be made of. Hence, through several iterations, the concept of the 'nucleus-space' was added to the learning unit, which proved itself to be helpful for students' acceptance of the unit. Indeed, our results show that this phrasing highlights the location aspect of the nucleus-space in an appropriate way and minimises potential misconceptions of a nucleus as an entity in its own right. In a similar way, the 'orbital-space' is introduced, which defines the space 'where it is likely to find electrons'. This aims at reenforcing the probability aspect of the orbital-space, while unambiguously avoiding any misleading notion of electrons orbiting around in planet-like circles.

In addition, within the learning unit, we make a clear distinction between 'particles' and 'particle systems'. This means that only elementary particles—leptons and quarks—are denoted as particles, while baryons and mesons are introduced as particle systems 'which are made of particles'. Our findings showed that, thanks to this minor modification, any potential misconceptions of protons enveloping quarks like jelly could be avoided. The important aspect of linguistic clarity is also supported by the use of typographic illustrations, which we present next.

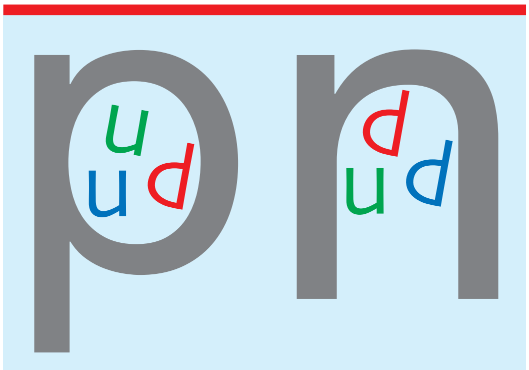

Figure 1. Typographic illustration of a proton and a neutron, as used in the first chapter of the learning unit.

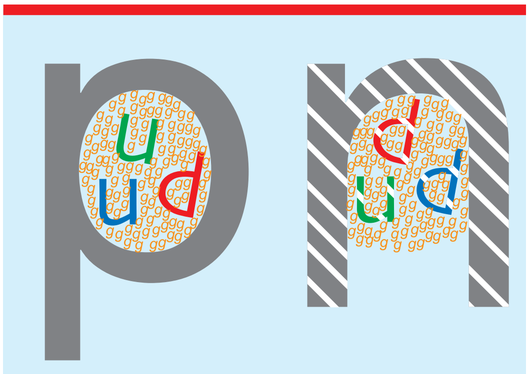

Figure 2. Typographic illustration of a proton and an antineutron, as used in the second chapter of the learning unit.

3.3. Typographic illustrations

Since education research shows that visual illustrations are essential to communicate scientific ideas in the classroom [19, 20], we developed new graphical representations of particles and particle systems to include in our learning unit. With the model aspect of particle physics in mind, these illustrations aim at visualising subatomic objects, while avoiding triggering any misconceptions about their potential appearance. Therefore, instead of using spheres or any other misleading symbols, we represent particles and particle systems by using their respective letters (see figure 1). To enable a clear distinction,

Figure 3. Typographic illustration of the atomic model, which highlights the distinction between the nucleus-space and the orbital-space.

elementary particles are drawn in colour, while particle systems are grey. Specifically, red, green, and blue are reserved for quarks, to set up the notion of colour charge early on, which will then be introduced within the learning unit's second chapter.

Furthermore, since the learning unit also includes the notion of antiparticles and systems of antiparticles, a graphical visualisation of anticolour charge was required. Here, we developed an alternative to the commonly used complementary-colour method, whereby antiparticles and antiparticle systems are identified through the use of stripes instead of a change in colour (see figure 2). The rationale of this novel approach is to avoid any overlapping of the content with previously established optics knowledge, as this can be expected to be detrimental to learning. Instead, by using stripes, a clear distinction between particles and antiparticles is given, which also facilitates students' understanding of the model aspect of particle physics. Indeed, our alternative representation of anticolour charge was tested with high school students (age group 16–17 years, $n = 42$) and physics teachers ($n = 38$), who evaluated it to be a more helpful way of distinguishing between colour charge and anticolour charge [21]. Specifically, both groups judged the use of the stripe pattern to be easier to understand, more informative, and simpler. In addition, the students and the teachers reported needing drastically less time to answer the questions in the questionnaire. It is in this sense that the use of a stripe pattern in representations of anticolour charge proved itself to be particularly helpful for learning.

To represent the atomic model, which is introduced in the learning unit's first chapter, a typographic illustration is used as well (see figure 3). Its aim is to qualitatively represent an atom and to highlight the difference between the nucleus-space and the orbital-space. In subsequent steps, this illustration of the atomic model allows the introduction of different orbital shapes within the orbital-space, without using inadequate terms, such as orbits or shells. To demonstrate a more realistic size ratio, however, the additional use of interactive animations and animated movies may be required.

4. Conclusions and implications

The learning unit on the subatomic structure of matter presented here was developed and evaluated with 12 year-olds over the course of several iteration cycles [2]. At the end of the development process, a detailed annotated version of the unit's first chapter was published in German [22]. An English version of the learning unit is currently under development and will be made available on request.

In addition, we also introduced the final version of the learning unit to experienced physics teachers within designed professional development programmes to document their assessment of the unit. During these programmes, teachers were instructed about the main concepts and key ideas of the learning unit, and were encouraged to discuss students' conceptions about particles among each other. Next, based on a research manual, teachers were introduced to the technique of probing acceptance, which we used to develop the learning unit. This enabled them to conduct one-on-one interviews with grade-6 students during the last part of the professional development programme to evaluate the feasibility of the learning unit on their own. The analysis of the teachers' one-on-one interviews led to comparable results as documented during our initial study and showed the learning unit to be adequate for a broad evaluation in the classroom. In addition, all teachers provided us with very positive feedback and evaluated the unit's key ideas and main concepts to be promising for classroom application [23]. Specifically, the typographic illustrations and the use of certain key words and key phrasings, for example to distinguish between particles and particle systems, appealed greatly to all teachers and were identified as important for the introduction of subatomic particles in the classroom. Hence, based on our results, we concluded that it is indeed possible and useful to introduce elementary particles in early physics education.

However, we want to stress the fact that we do not limit our learning unit to the use with 12 year-olds. In fact, since the contents of the unit were developed with grade-6 students, who had no prior knowledge about the subatomic structure of matter, we consider the use of the learning unit to be independent of age. Furthermore, our findings highlight that to provide learners with adequate and meaningful learning offers, an iterative development of such learning material by means of design-based research is essential.

Last, we want to conclude by giving a brief overview of the most important implications of our research, which we consider to be highly promising for classroom application:

- Before discussing the topic of particle physics in the classroom, care should be taken to properly introduce and define the term 'particle'. We suggest to only use it for the description of elementary particles, since our results showed that students have difficulties to imagine particles 'within' particles. Instead, so-called 'composite particles' can be elegantly introduced as particle systems, which are made of particles.
- Abstract symbols, like the typographic illustrations presented here, are well-suited for the graphical representation of particles. Specifically, compared to the commonly used spheres, their use minimises the triggering of misconceptions about the appearance of particles. Furthermore, avoiding any pseudo-realistic illustrations and instead focusing on abstract symbols supports an adequate introduction of the model aspect of science in the classroom.
- Introducing the 'nucleus-space', instead of the standard description of the 'nucleus', greatly facilitates the discussion of a modern atomic model. Indeed, adding the word 'space' to the key term 'nucleus' emphasises its location aspect, while at the same time hindering the formation of potential misconceptions about the nucleus as an entity in and of itself. Consequently, this enables an elegant introduction of protons und neutrons, which are located in the nucleus-space.
- In a similar way, the introduction of the key term 'orbital-space' turned out to be very helpful for students' understanding of an accurate atomic model. Specifically, to avoid triggering any misconceptions of shells or orbits, it is worthwhile to introduce the notion of orbitals from the beginning. The 'orbital-space' is then defined as the space in which it is likely to find electrons. Doing so emphasises the probability aspect of the description of subatomic particles and facili-

tates the development of a coherent theory of orbitals at a later stage in the curriculum.

- Dividing the atomic model into two different areas and thus highlighting its location and probability aspect also allows to elegantly introduce empty space as the counterpart to elementary particles. Our findings showed that emphasising the nucleus-space and the orbital-space as empty spaces, where it is likely to find particles, appealed greatly to students. Indeed, during our research we did not document any statements questioning the 'fabric' of atoms and most students even evaluated the notion of empty space to be intriguing rather than difficult to accept.

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