PROCEEDINGS OF SCIENCE
ONLINE ICRC 2021 THE ASTROPARTICLE PHYSICS CONFERENCE Berlin | Germany
37th International Cosmic Ray Conference 12–23 July 2021

Making Particle Physics and Cosmology Accessible for High School Students

PoS(ICRC2021)1369

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In teaching science, you often need to decide on how far to introduce students to topics from an abstract scientific and mathematical perspective. Considering this question, we developed and tested educational materials on Particle Physics and Cosmology for students of grade 9 to 12 at secondary and upper secondary level, and for gifted students in special courses or academies, like Deutsche Schülerakademie or competitions like Jugend forscht, building on their prior knowledge. Our material also contains experiments supported by DESY and the University of Wuppertal. The theoretical parts of our course material cover electromagnetism and quantum mechanics up to Maxwell's equations, the Schrödinger equation and the Klein-Gordon equation, which require basic knowledge in differential equations and group theory. Some course participants were introduced to geometrical path lengths, tensors, and symmetries (according to [4], [12]).
The evaluation of the results, the material, and the courses from a cognitive as well as a psychological point of view unfolds possibilities and necessities to elaborate on different parts of exercises and projects on different levels, and revealed new relations between these parts. Students' perception of physics and mathematics, their beliefs in understanding something and their workout of projects indicated relationships different from our expectations ([10], [11]). Results in connection with different types of courses are described below for experiments on (i) *Differential Equations*, (ii) *Path Length* and (iii) *Symmetries*. The topics are described in connection with courses, activities, or students' projects.

37[th] *International Cosmic Ray Conference (ICRC 2021)*
July 12th – 23rd, 2021
Online – Berlin, Germany

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1. Introduction

Often the question appeared, how to motivate students for cosmology and particle physics at secondary school and high school. Students' motivation goes hand in hand with understanding and psychological components, s. [8]. Furthermore students often stick to their own results from the beginning ([10]). Results in exercises or projects depend on students' abilities in self-regulation ([13]). Self-regulated learning begins with start and stop when the goals set before are reached. But what about the steps in between? Students need to find their way to the goal. In school, students often solve exercises with special algorithms or work out exercises or projects “straight ahead". Based on [11], we will describe our experience with teaching sequences in cosmology and particle physics and also take a look at the psychological components in connection with self-regulated learning, students' beliefs, and results in projects.

2. Theory and Design

The results presented here are based on the author's courses and working groups for students from grade 10 to 13, held between 2014 and 2021. The qualitative data was collected between 2013 and 2015 in the author's project courses, which are part of hin PhD research ([10])

The contents of the different courses and projects differ from each other, but parts of the processed topics of the courses are similar. These topics cover: (i) Relativity, (ii) Fields, (iii) Electrodynamics, (iv) Strong Interaction, (v) Weak Interaction, (vi) Symmetries, (vii) Standardmodel of Particle Physics.

2.1 Structure of Courses

2.1.1 Jugend forscht

Jugend forscht is Germany's most famous junior science contest, for students aged 15 to 21 years, researching their own projects. Research topics are divided between physics, mathematics/computer science, and other sciences (see `https://www.jugend-forscht.de/`).

Categories of research are divided into the classes of physics, mathematics/computer science, and other sciences. Students are allowed to accept support from universities or engineering companies. The competition start locally, continue at regional level and finish at national level.

From 2019 to 2021, the author mentored three teams working on cosmology and particle physics. The specific topics were (1) Simulation of cosmic rays with the Wassersteim-GAN, (2) Effects of different parameters on experiments with a Kamiokande, (3) Simulation of cosmic ray with Wasserstein-GA networks supported by Julian Rautenberg from the Bergische Universität Wuppertal.

2.1.2 Deutsche Schülerakademie

Gifted students from grades 10 to 12 are selected and offered summer courses covering different topics (`https://www.schuelerakademien.de/`). Together with C. Neugebauer, the author conducted a course on *Cosmology and Particle Physics* in 2013. By support of DESY (represented by Carolin Schwerdt) they could use the student experiments with Kamiokande, CosMO-detectors and Cloud Chamber.

Figure 1: Curved space in two dimensions

2.1.3 Project Courses

Project courses are courses where deeper scientific work is learned and practiced ([9]). Schools are involved to establish the courses about special topics beyond the usual topics of the curriculum and in connection to another topic or application. Project courses take place over a school year during the last two school years at secondary school, in grade 11 or 12. The choice of topics for projects under the given concept of the course is left to students without immediate connection to usual lessons in **s**cience, **t**echnology, **e**ngineering, and **m**athematics (STEM).

In the school years 2013/2014 and 2014/2015, the author taught three project courses about *cosmology and particle physics*, together with 17 students, and four project courses about *coding and cryptography*, with 21 students, collecting research data.

2.1.4 Physics in Secondary School

According to [5], astrophysics and particle physics can be seen as extensions of relativity and quantum phyics in high school. Even the Schrödinger equation of the simple style (type 1 from below) is a priori not explicitly included in the curricula of most federal states of Germany.

3. Theoretical Physics and Mathematics

3.1 Topics in Courses

Here we will concentrate on project courses and the course of the Deutsche Schülerakademie where students worked out projects in groups of two participants. Typical topics for students' projects in project courses or the Deutsche Schülerakademie in physics besides the topics mentioned in section 2 are (i) *comparison of structure of different fields*, (ii) *tensors*, (iii) *structure of accellerators*.

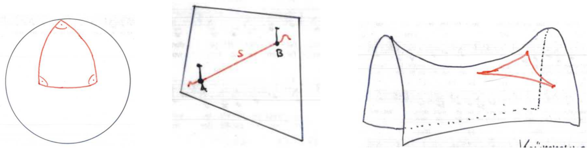
3.2 Technical Categorisation

For characterisation and comparison we chose the mathematical topics (i) *differential equations*, (ii) *symmetries*, and (iii) *path length* and examine which of the topics appear in the project themes the students choose to work on.

3.3 Path Length

The introduction to path length (PL) took place in the following four types:

1. Referring to [2], [6] and [7] a curved space can be conceptialized by wrinkling a paper and projecting itto the plane. It is a "curved space in practice" (s. figure 1).



$> 180°, k > 0$ $= 180°, k = 0$ $< 180°, k < 0$

Figure 2: Three cases of curved space

	PL 1	PL 2	PL 3	PL 4
Jugend forscht	−	+	+	−
Deutsche Schülerakademie	+	+	+	+
Project Course	+	+	−	−
Physics in lessons	+	+	−	−

Table 1: Treatment of path length (PL) in upper secondary school; ("+": covered, "−": not covered)

2. A geodesic is the shortest connection between points in space. We need to distinguish between three cases of spaces in connection with their curvature k: (1) whithout curvature ($k = 0$), sum of angles in triangle = 180°, which is the imagination of dayly live; (2) positive curved space ($k > 0$), sum of angles in triangle > 180°, which is imaginable from atlas; (3) negative curved space $k < 0$, sum of angles in triangle < 180°, conceivable as horse seat. The three cases are shown in the figure 2 (similar to [6]).

3. To have a better overview, computer algebra systems can help with visualizations. (For details see [11].)

4. Infinitesimal increment picturesque in different coordinate systems are the *cartesien coordinate system* with $s^2 = x^2 + y^2$, the *infinitesimale coordinate system* with $ds^2 = dx^2 + dy^2$ and the *translation into calculus* by $ds = \frac{\partial x}{\partial \tilde{x}} d\tilde{x} + \frac{\partial y}{\partial \tilde{y}} d\tilde{y}$.

5. Infinitesimal increment $ds^2 = \sum_{i,k=1}^{n} g_{ik} dx_i x_k$ for $n = 2, 3$, transformations included, e.g. carthesian coordinate system and polar coordinate system:

$$\begin{aligned} x_1 &= r \cdot \sin\theta \cdot \cos\phi\,, \\ x_2 &= r \cdot \sin\theta \cdot \sin\phi\,, \\ x_3 &= r \cdot \cos\theta\,, \end{aligned} \qquad \text{and tensor} \quad \{g_{ij}\} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & r^2 & 0 \\ 0 & 0 & r^2 \cdot \sin^2(\theta) \end{pmatrix}$$

Table 1 gives an overview of which courses wired path length.

3.4 Differential Equations

In upper secondary school might appear the following physical differential equations (DE):

1. Schrödinger equation type 1: $\psi''(x) + \frac{8\pi^2 m_e}{h^2}(E - E_{pot}(x)) \cdot \psi(x) = 0$ or numerical approximation via $\psi(x_{n+1}) = \psi(x_n) + \psi''(x_n) \cdot \Delta x$

	DE 1	DE 2	DE 3	DE 4
Jugend forscht	+	−	−	−
Deutsche Schülerakademie	−	+	+	+
Project Course	+	−	+	+
Physics in Lessons	+	−	−	−

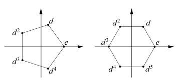
Table 2: Treatment of differential equations (DE) in upper secondary school ("+": covered, "−": not covered)

2. Schrödinger equation type 2: $\left(-\frac{\hbar}{2m}\nabla^2 + V(\vec{r})\right)\psi(\vec{r}) = E\psi(\vec{r})$.
3. Maxwell's equations: $\nabla \cdot \vec{E} = \varrho, \quad \nabla \cdot \vec{B} = 0, \quad \nabla \times \vec{E} = -\frac{1}{c} \cdot \frac{\partial \vec{B}}{\partial t}, \quad \nabla \times \vec{B} = \frac{1}{c} \cdot \frac{\partial \vec{E}}{\partial t}$
4. Klein-Gordon equation: $\left(\frac{\partial^2}{\partial t^2} - c^2 \cdot \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\right) + \frac{m^2 c^4}{\hbar^2}\right)\Phi(\vec{r}, t) = 0$

Differential equations can be used to describe the structure of systems, by a calculus perspective or by a graphic perspecive. Some of the DE reveal the structure of fields by their symmetries and the structure of the equation itself. For example the Klein-Gordon equations illustrates the symmetry in the x-, y- and z-axes. Information about usage in curses are shown in table 2.

3.5 Symmetries

In every course we take a look at symmetries (S). Here we disregard the colour of quarks and the preservation of the probability. Symmetries can appear via the following five aspects:

1. Figure: 

   You can simply describe symmetry via figures, ignoring coordinate systems. When we utilize vectors, coordinate systems can be included, too..

2. Matrices for rotation and reflection: $\begin{pmatrix} \cos(\varphi_n) & -\sin(\varphi_n) \\ \sin(\varphi_n) & \cos(\varphi_n) \end{pmatrix}$

   In mathematic education from grade 11 to 13, rotations and reflections are described by matrices.

3. Exponential function: $\exp(\mathrm{i} \cdot \varphi)$, interpretation as rotation included.

   (Gifted) students are introduced to complex numbers, so they can work with complex exponential function for describing rotation.

4. Groups as $SO(n)$, including groups characteristics.

   After describing rotation and reflection with matrices in aspect 2, rotation and reflection groups can be introduced.

5. **C**harge, **P**arity, **T**ime-symmetry

   Everything of CPT is possible with graphic description. In P and C we do not need complex numbers, so that it is possible with the complex exponential function.

Table 3 gives an overview which of the author's courses covered symmetrie.

	S 1	S 2	S 3	S 4	S 5
Jugend forscht	+	+	−	+	−
Deutsche Schülerakademie	+	+	+	+	+
Project Course	+	+	−	−	−
Physics Lessons	+	−	−	−	−

Table 3: Treatment of symmetries (S) in upper secondary school (“+": covered, “−": not covered)

4. Experimental Physics

Possibilities of experiments in cosmology and particle physics in secondary school are limited. As remarked above, the project courses and the courses of the Deutsche Schülerakademie had the possibilities to use Kamiokande, CosMO-detectors, and Cloud Chamber. The possibillity for the use of Kamiokande was given for the rest of the courses, too. Apart from these experiments, the courses used several videos of CERN and DESY and contents of Masterclasses (`https://www.desy.de/schule/schuelerlabore/`) in connection with experiments.

5. Research

5.1 Design of the Study

Research on the project courses included the exploration of students' self-regulated learning, results in projects and epistemological beliefs. Data was collected on: Students' (i) *definition of physics and mathematics*, their (ii) *beliefs in understanding*, their (iii) *workout of projects* and connections between them appered to be important. (For details concerning the data mentioned here see [10], [11].)

- **Definitions of Physics or Mathematics (DPM).** Definition as *abstract science*, e.g. via “physics as support for different (applied) sciences", or via *applications*, f.e. by “physics for everything all over the world."

- **Beliefs in Understanding in Reflective Thinking (RT).** During the data analysis two different types appeared as important. They are distingishes by keywords in the interviews: active via *explain*, *apply* and passive: via *observe*, *reproduce*.

- **Workout of Projects (WO).** Students' workout might be characterised by an emphasis on *abstract* or on *application*, e.g. an *abstract* workout of projects about symmetry with groups or a workout in connection with *applications* as the execution of the Kamiokande experiment.

5.2 Results

It turned out that two special cases of the triple with definition of physics and mathematics, epistemological beliefs in understanding and workout of project appeared ([11]):

- Type 1: Students defined physics via applications and described physics understanding as active reflective thinking $\rightsquigarrow$ they chose an abstract topic for their project.

Type	**DPM**	**RT**	**WO**	**# (%)**
1	application	active	abstract	7, (41 %)
2	abstract	passive	application	7, (41 %)

Table 4: Data of project courses in physics

Type	**DPM**	**RT**	**WO**	**# (%)**
1	application	active	abstract	18, (47 %)
2	abstract	passive	application	14, (37 %)

Table 5: Data of project courses, physics and mathematics combined

- Type 2: Students defined physics in an abstract discipline and described physics understanding as passive reflective thinking $\rightsquigarrow$ they chose an application for their project.

Tables 4 and 5 shows the frequencies of these tripls. Table 4 shows the data only for the 17 project courses in physics. 14 of these 17 students belong to type 1 or type 2, only three of them to the other cases. This result is supported when considering the 21 students of the project courses in mathematics (see table 5). So, 32 of the 38 students from all the courses belong to these two types (for details see [11]).

6. Conclusion

Students are able to decide between different possibilities by themselves for the choices of the topics and the type of workout of their projects. They are given the choice to workout their projects in two different styles: only experimental / practical type or only theoretical / abstract type. Both types together did not appear at all. Only a few different types appeared too.

There are a lot of possibilities to reach foundations of cosmology and particle physics. Students' motivation is changeable and depends on their options to choose a topic for their project – or a combination of topics. Their exercises should give them possibilities for appropriate workout.

Teachers should look for possibilities to enable students to divide projects into different topic areas to elaborate upon at different levels, and offer alternative choices for each topic. When deciding on teachin moves, teachers should keep in mind students' beliefs in understanding and their perception of physics (or STEM in general) and consider them for project activities.

Teachers need specialized background in STEM to be able to offer students alternative projects and activities. Therefore Stoffdidaktik is indispensable ([3]).

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