Making Particle Physics and Cosmology Accessible for High School Students

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Introduction

In teaching science, you often need to decide on how far to introduce students to topics from an abstract scientific and mathematical perspective. Considering to 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 academies as 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, 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 Ellwanger, 2012; Wong, 2013).
Evaluation of the results, the material, and the courses from a cognitive as well as a psychological point of view unfold possibilities and necessities to elaborate on different parts of exercises and projects on different levels, and they 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 expections (Stoppel, 2019, 2021). 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.

Types and Structure of Courses

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. Types of courses:

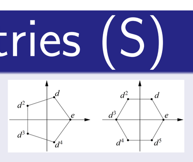
- **Jugend forscht**
  Jugend forscht is Germany's most famous junior science contest, for students aged 15 to 21 years, researching their own projects. Research topics are divided between physics, mathematics/computer science, and other sciences.
  From 2019 to 2021, the author mentored three teams 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 Bergische Universität Wuppertal.
- **Deutsche Schülerakademie**
  Gifted students from grades 10 to 12 are selected and offered summer courses covering different topics.
  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.
- **Project Courses**
  Courses for deeper scientific work (Schulentwicklung NRW, 2010) over a school year in grade 11 or 12.
  In the school years 2013/2014 and 2014/2015, the author taught courses about *cosmology and particle physics* with 17 students, collecting interesting data.
- **Physics in Upper Secondary School**
  According to KMK (2020, p. 19f) astrophysics and particle physics can be seen as extensions of relativity and quantum phyics in upper secondary lessons.
- Typical topics for students' projects in project courses and academies for gifted students in connection with cosmology and particle physics: *Relativity, Fields, Electrodynamics, Strong Interaction, Weak Interaction, Symmetries, Standard Model of Particle Physics, comparison of structure of different fields, tensors* and *the structure of accelerators*.

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 $\psi(x_n + 1) = \psi(x_n) + \psi''(x_n) \cdot \Delta x$
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: $\nabla \cdot \vec{E} = \varrho$, $\nabla \cdot \vec{B} = 0$, $\nabla \times \vec{E} = -\frac{1}{c} \cdot \frac{\partial \vec{B}}{\partial t}$, $\nabla \times \vec{B} = \frac{1}{c} \cdot \frac{\partial \vec{E}}{\partial t}$
4. Klein-Gordon Equation:
   $\left(\frac{\partial^2}{\partial t^2} - c^2 \cdot \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\right) + \frac{m^2 c^4}{\hbar^2}\right)\Phi(\vec{r}, t) = 0$

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

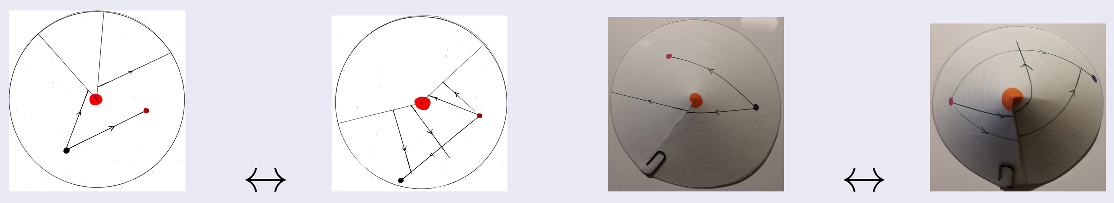
Symmetries (S)

1. Figure: 
2. Matrices for rotation and reflection: $\begin{pmatrix} \cos(\varphi_n) & -\sin(\varphi_n) \\ \sin(\varphi_n) & \cos(\varphi_n) \end{pmatrix}$
3. Exponential function: $\exp(\mathrm{i} \cdot \varphi)$, interpretation as rotation included
4. Groups as $SO(n)$, characteristics as groups included
5. **C**harge, **P**arity, **T**ime-symmetry

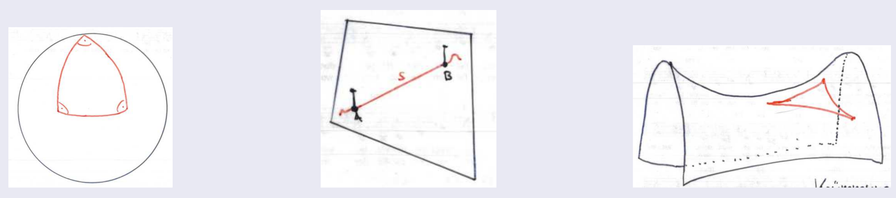
	S 1	S 2	S 3	S 4	S 5
Jugend forscht	+	+	−	+	−
Deutsche Schülerakademie	+	+	+	+	+
Project Course	+	+	−	−	−
Physics Lessons	+	−	−	−	−

Path Length (PL)

1. Curved space in praxis

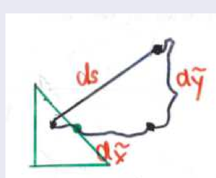


2. Geodesic with a perspective on curvature
   - Shortest connection between points in space
   - Distiction between three cases:
     1. Whithout curvature $k = 0$; sum of angles in triangle $= 180°$ ⇝ the imagination of daily live
     2. Positive curved space $k > 0$; sum of angles in triangle $> 180°$ ⇝ imaginable from atlas
     3. Negative curved space $k < 0$; sum of angles in triangle $< 180°$ ⇝ horse seat



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

3. Illustration under usage of computer algebra system
4. Infinitesimal increment picturesque



cartesian coordinate system:
$s^2 = x^2 + y^2$
infinitesimal coordinate system:
$ds^2 = dx^2 + dy^2$
translation into calculus:
$$ds = \frac{\partial x}{\partial \tilde{x}} d\tilde{x} + \frac{\partial y}{\partial \tilde{y}} d\tilde{y}$$

5. Infinitesimal increment with calculus
$$ds^2 = \sum_{i,k=1}^{n} g_{ik} dx_i x_k \quad \text{for } n = 2, 3$$

transformations included, e.g.b. carthesian coordinate system and polar coordinate system: $x_1 = r \cdot \cos\varphi$, $x_2 = r \cdot \sin\varphi$.
$$ds^2 = dx_1^2 + dx_2^2 = dr^2 + r^2 d\varphi^2.$$
and tensor
$$\{g_{ij}\} = \begin{pmatrix} 1 & 0 \\ 0 & r^2 \end{pmatrix}$$

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

Design of the Study

Students' Beliefs and Self-regulated Learning

It turned out that students' (i) *definition of physics and mathematics*, their (ii) *beliefs in understanding and connections between them* and their (iii) *workout of projects* are important factors. (Stoppel, 2019).

Definitions of Physics or Mathematics (DPM)

- Definition as abstract science
  - "Physics as support for different (applied) sciences."
- Definition via applications
  - "Physics for everything all over the world."

Beliefs in Understanding via Reflective Thinking (RT)

active: *explain, apply*
passive: *observe, reproduce*

Workout of Projects (WO)

abstract: *symmetry with groups*
application: *Kamiokande experiment*

Special Cases

- Type 1: Students defined physics by its applications and described physical understanding as active reflective thinking ⇝ they chose an abstract topic for their project.
- Type 2: Students defined physics in an abstract discipline and described physical understanding as passive reflective thinking ⇝ they chose an application for their project.

Research Results

Description of scaling of data for analysis

- Courses and Groups of Physics

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

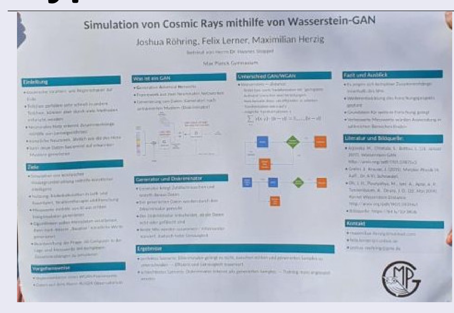
- Courses and Groups for Physics in combination with Mathematics

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

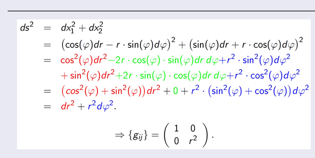
(Stoppel, 2019, 2021)

Students' Project Results

Type 1 of results

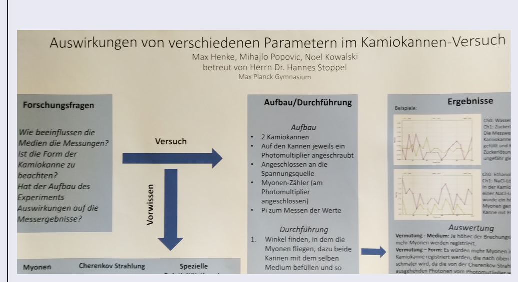


DE 2, PL 2 – 5, S 1, S 2, S 4

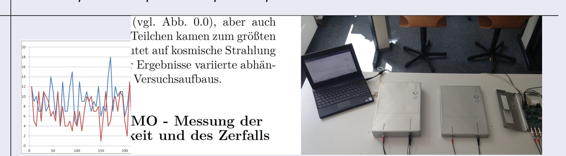


DE 2 – DE 4; PL 1 – PL 5; S 1 – S 5

Type 2 of results



DE 2, PL 2, PL 3, S 1, S 2



DE 2 – DE 4; PL 1 – PL 4; S 1, S 2

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.
- Students 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.
- 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.
- Students' activities should include possibilities for appropriate self-organized 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 (Dilling et al., 2020).

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