Creation of a Massive Open Online Course on Antimatter for Undergraduate STEM Students

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Abstract

In this report, we present a Massive Open Online Course on antimatter created during the CERN 2021 summer internship, aimed at undergraduate STEM students. We present the motivation, aims and objectives of such a project, its structure and its content. We highlight what we have achieved - the structure, slides, handouts and video lectures. We express what needs to be completed - the translation of the content in French and the filming of the lectures in a professional studio. Finally, we underline our experience of the project and of the internship more generally, discussing other aspects of this journey such as the lectures, the virtual visits and the social events.

1 Introduction

Whilst antimatter is so incredibly rare in the universe, its theoretical and practical applications in modern-day physics cannot be understated. At CERN, a number of experiments seek to study its properties and the way it interacts with matter - for instance, the Antihydrogen Laser Physics Apparatus (ALPHA) traps cold antihydrogen atoms to search for differences between the spectrum of hydrogen and that of its antimatter counterpart. Exploring the discrepancies between matter and antimatter is paramount to understand why there is so little antimatter in the universe.

Antimatter research is a broad field that covers many areas of physics. In ALPHA, plasma physics, laser physics and cryogenics are involved for the trapping, whilst spectroscopy and detector physics are needed to analyse the properties and the stability of the antihydrogen. Other areas of research relevant to antimatter involve nuclear physics, biophysics, astrophysics and general relativity; hence, it can be challenging to grasp the ins and outs of contemporary antimatter research.

1.1 Motivation

The complexity of modern antimatter research and the advanced mathematics required to fully comprehend the topic contribute in making it very much ill-understood to the public. One may believe antimatter to be a science-fiction concept, or mistake it for something it is not (dark matter, dark energy...); there is certainly a sense of mystery surrounding this field of particle physics, even almost a century after its prediction and first discovery.

There is a real need to make antimatter physics more approachable and less obscure to the public, and more specifically to university students. Indeed, antimatter is not only of interest for theoretical purposes: it has real-life applications in biophysics and medical sciences for instance. Demystifying the origins and the extent of antimatter research is thus important, not only for funding purposes to explore the biggest questions of our universe, but also to attract the attention of the public on the fact that fundamental research

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is not a waste of money and of time - thousands of lives are saved by the results of antimatter research (e.g. through PET scanners), there are several important applications in engineering and material sciences which help society as a whole, etc.

In particular, it is important to introduce antimatter research to students in other STEM subjects. Indeed, since antimatter research branches with a wide array of other fields of science, whether in other areas of physics, engineering, biology or chemistry, we think it is of great benefit to not only attract students to this very interesting field, but also to introduce them to concepts that they may encounter in their respective fields of research. Thus, we came up with the idea to create a Massive Open Online Course (MOOC) called “Introduction to Antimatter Physics”, in order to make the history of antimatter research, the theory behind antimatter physics and the cutting-edge research questions and experiments approachable and interesting for such an audience.

1.2 Aims and Objectives

The aim of this project is to deliver a university-level course to UK A-level (17/18 year old) or equivalent and first or second year undergraduate STEM students on antimatter. We believe that the best method to offer a taste of antimatter physics to the largest number of students around the world is through the creation of a MOOC, in English and potentially in other languages like French as well. Since MOOCs are often free to access for university students and for people coming from disadvantaged backgrounds, we believe it is very well suited for the dissemination of knowledge.

The process of creating a MOOC is composed of several objectives - the first of which is to determine its structure. Crucial to a MOOC is obviously the video lectures - these are supported by presentations (made in LaTeX/Beamer). Additional lecture notes / handouts are also useful for students to digest the material and go further. These steps were undertaken one at a time, and assembling all the material produced a homogeneous MOOC that met our expectations.

2 The MOOC

2.1 Structure

There are 8 weeks in the MOOC, which corresponds to the average number of sections in university-level MOOCs, and is adequate for an introduction to the subject. In each week is included two to four lecture videos, a recap video summarising the content seen in the week, a handout exploring the week’s content in more details, and, in principle, a question and answer section for students to interact with teaching staff and amongst themselves should they have any questions or comments.

Each lecture video is 10-20 minutes long, which mirrors usual university online lectures, and is appropriate to catch the students’ attentions without being too short or too long. In these videos, the content is presented using the support of a PowerPoint-like presentation (made in Beamer for even more professionalism), with the pdfs of the presentations made available to students for them to follow and go through for revision. The lecturer is also visible in the videos via webcam capture, as it is often more comfortable to see who is presenting the content.

The handouts have the format of usual lecture notes, with sections highlighting the topics covered, important concepts and equations explained thoroughly, and supplementary information that goes beyond the scope of the video lectures for the interested reader to look at. Furthermore, additional tasks and questions are provided, directing the readers to supplementary resources and helping the students digest the content.

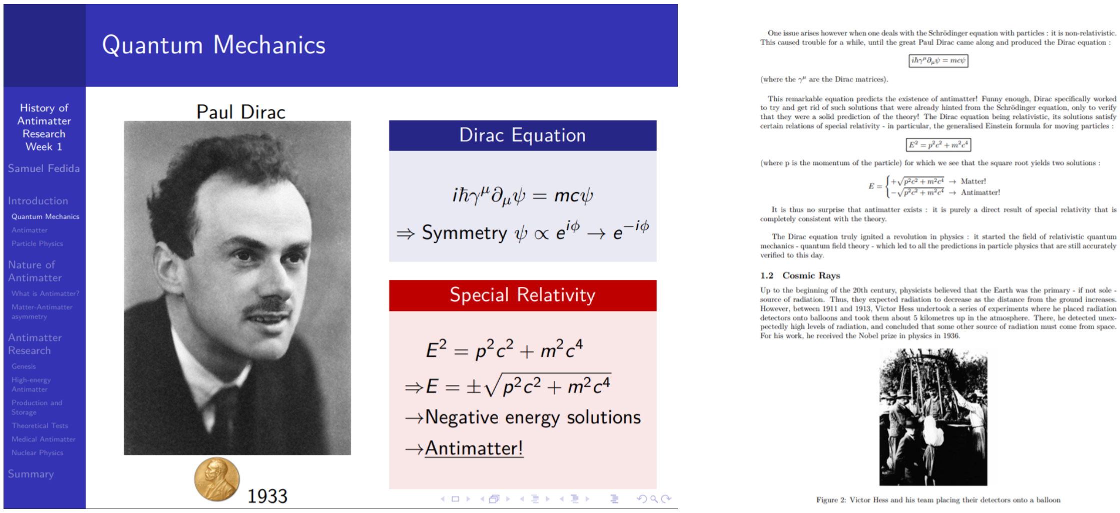
2.2 Content

The MOOC is divided into 8 sections (1 per week), and the syllabus is as follows :

1. History of Antimatter Research
   - History of Quantum Mechanics
   - Nature of Antimatter
   - Evolution of Antimatter Research
2. Particle Physics
   - The Standard Model
   - Feynman Diagrams
3. Particle Detectors
   - General Purpose Detectors
   - Particle Interactions and Quantum Effects
4. Experimental Methods for Antimatter Physics
   - Particle Traps
   - Trapping and Cooling
5. Frontier of Antimatter Research I
   - Antimatter Production and Storage
   - Theoretical Tests on Antimatter
   - Antimatter and Gravity
6. Frontier of Antimatter Research II
   - Antimatter and Nuclear Physics
   - Antimatter Research in Space
   - High-Energy Antimatter Research
7. Applications of Antimatter
   - Medical Antimatter
   - Industrial Uses
8. Frontier of Antimatter Research III
   - Interferometry for antimatter
   - Tests of CPT Symmetry

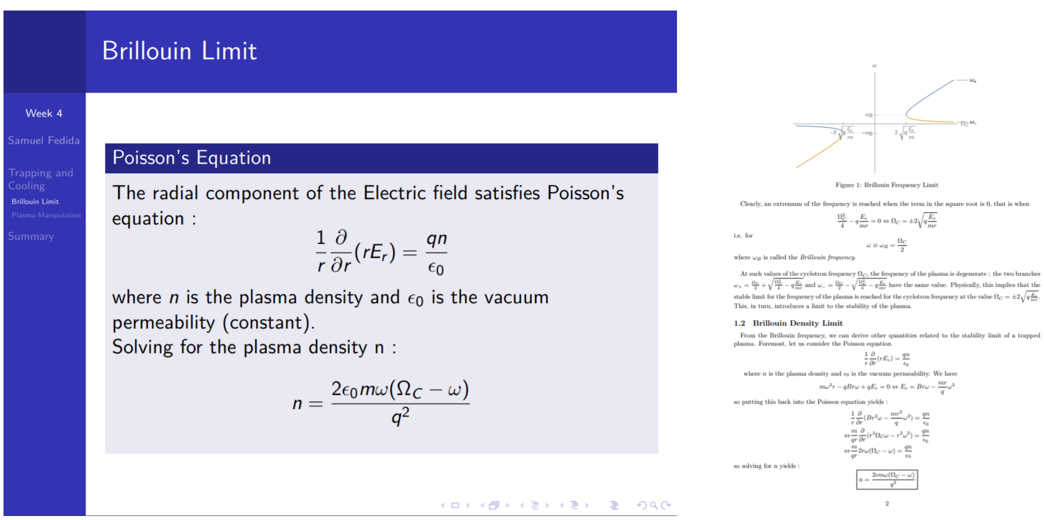
Two lecturers presented the various topics covered in this MOOC : Ahmed Al-Kharusi (another CERN summer student), and myself. Ahmed covered weeks 2, 3, 4 part I (Particle Traps), 5 and 8, whilst I produced and presented weeks 1, 4 part II (Trapping and Cooling), 6 and 7.

In Week 1, we first present the early history of quantum mechanics and of particle physics up to the 1960s-1970s, where we highlight the theoretical as well as the experimental breakthroughs made during that period of time. We then give an introduction of what antimatter is and what it is not, underlining its similarities and differences with regular matter. We give a short presentation of cosmology into the Sakharov conditions in Baryogenesis, and we explain the symmetry violations of the weak interaction. Finally, we give a review of the evolution of antimatter research, showing how it became so diverse with time. These three parts of Week 1 are divided into 3 videos - 13 minutes, 20 minutes and 18 minutes-long, respectively, with one 2 minutes-long summary video; with 31 slides and a 10 pages-long handout.



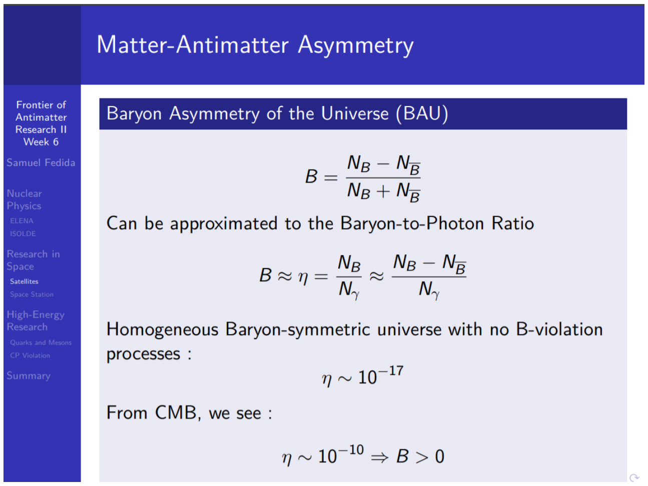
Left : Slide from the Week 1 presentation, Right : Extract from the Week 1 Handout

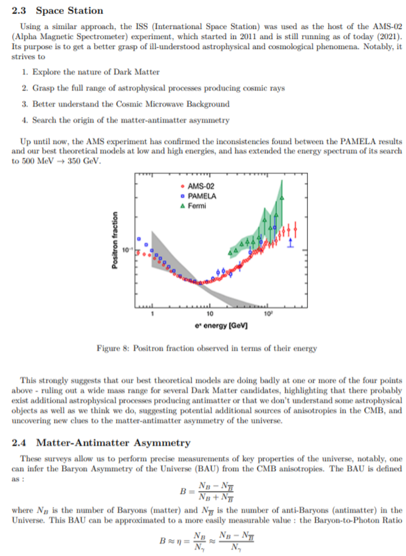
In recent years, several experiments at the CERN Antiproton Decelerator (AD) have made significant advances in trapping and probing low-energy positrons and antiprotons. In the second part of Week 4, we explore this topic by presenting several technical aspects of trapping and cooling antimatter in particle traps. Notably, we derive the Brillouin limit for plasmas in Penning Traps, we highlight the ways to manipulate and cool plasmas, and we show how to determine the temperature of a plasma via temperature diagnostics. This second part of week 4 is presented in one 15 minutes-long video and one 1 minute-long summary video, with 12 slides and a 5 pages-long handout.



Left : Slide from the Week 4 presentation, Right : Extract from the Week 4 Handout

In Week 6, we present the frontier of antimatter research in the fields of nuclear, astro- and high-energy physics. Foremost, we introduce the PUMA project with the ELENA and ISOLDE experiments. Secondly, we exhibit the various questions involved in cosmological antimatter such as the Baryon Asymmetry of the Universe (BAU), and we present the results of the PAMELA and AMS-02 experiments. Finally, we go on to high-energy research with the LHCb experiment, presenting quarks and mesons, highlighting B-Bbar oscillations as a way to test for Charge Conjugation-Parity (CP) asymmetry, and showing more recent results with the muon results. This week is divided into these three sections, with videos being 12, 20 and 14 minutes-long, respectively, one 1 minute-long summary video, with 60 slides and an 8 pages-long handout.





2.3 Space Station

Using a similar approach, the ISS (International Space Station) was used as the host of the AMS-02 (Alpha Magnetic Spectrometer) experiment, which started in 2011 and is still running as of today (2021). Its purpose is to get a better grasp of ill-understood astrophysical and cosmological phenomena. Notably, it strives to

1. Explore the nature of Dark Matter
2. Grasp the full range of astrophysical processes producing cosmic rays
3. Better understand the Cosmic Microwave Background
4. Search the origin of the matter-antimatter asymmetry

Up until now, the AMS experiment has confirmed the inconsistencies found between the PAMELA results and our best theoretical models at low and high energies, and has extended the energy spectrum of its search to 500 MeV $\rightarrow$ 350 GeV.

Figure 8: Positron fraction observed in terms of their energy

This strongly suggests that our best theoretical models are doing badly at one or more of the four points above - ruling out a wide mass range for several Dark Matter candidates, highlighting that there probably exist additional astrophysical processes producing antimatter or that we don't understand some astrophysical objects as well as we think we do, suggesting potential additional sources of anisotropies in the CMB, and uncovering new clues to the matter-antimatter asymmetry of the universe.

2.4 Matter-Antimatter Asymmetry

These surveys allow us to perform precise measurements of key properties of the universe, notably, one can infer the Baryon Asymmetry of the Universe (BAU) from the CMB anisotropies. The BAU is defined as :

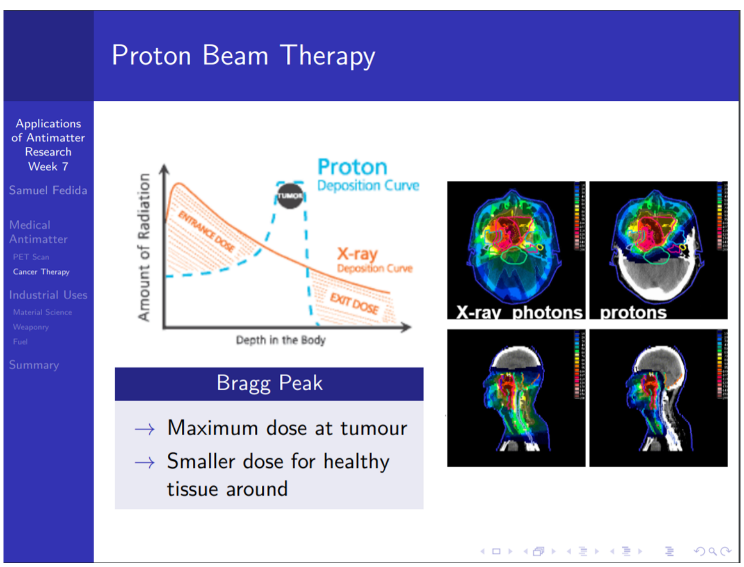
$$B = \frac{N_B - N_{\overline{B}}}{N_B + N_{\overline{B}}}$$

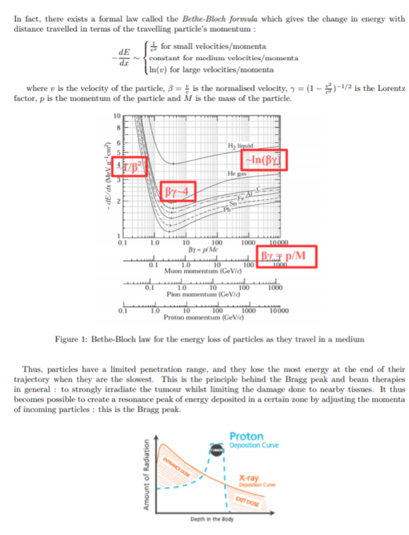
where N_B is the number of Baryons (matter) and $N_{\overline{B}}$ is the number of anti-Baryons (antimatter) in the Universe. This BAU can be approximated to a more easily measurable value : the Baryon-to-Photon Ratio

$$B \approx \eta = \frac{N_B}{N_\gamma} \approx \frac{N_B - N_{\overline{B}}}{N_\gamma}$$

Left : Slide from the Week 6 presentation, Right : Extract from the Week 6 Handout

In Week 7, we present the applications of antimatter into two sections : medical antimatter and industrial antimatter. In the medical antimatter section, we present Positron Emission Tomography (PET) scanners, proton beam therapies and the ACE experiment with antiproton beam therapy. In the industrial antimatter section, we show the potential of antimatter for uses in material science with Positron Annihilation Spectroscopy (PAS), we explore potential uses in weaponry via a US air force project, showing that theoretical limits make it extremely impractical for such uses, and we highlight the fact that antimatter is also not even remotely ready to be used as a fuel. The content of this week is contained into 2 videos - both 19 minutes-long, one 3 minutes-long summary video, with 24 slides and a 6 pages-long handout.





In fact, there exists a formal law called the *Bethe-Bloch formula* which gives the change in energy with distance travelled in terms of the travelling particle's momentum :

$$-\frac{dE}{dx} \sim \begin{cases} \frac{1}{v^2} \text{ for small velocities/momenta} \\ \text{constant for medium velocities/momenta} \\ \ln(v) \text{ for large velocities/momenta} \end{cases}$$

where v is the velocity of the particle, $\beta = \frac{v}{c}$ is the normalised velocity, $\gamma = (1 - \frac{v^2}{c^2})^{-1/2}$ is the Lorentz factor, p is the momentum of the particle and M is the mass of the particle.

Figure 1: Bethe-Bloch law for the energy loss of particles as they travel in a medium

Thus, particles have a limited penetration range, and they lose the most energy at the end of their trajectory when they are the slowest. This is the principle behind the Bragg peak and beam therapies in general : to strongly irradiate the tumour whilst limiting the damage done to nearby tissues. It thus becomes possible to create a resonance peak of energy deposited in a certain zone by adjusting the momenta of incoming particles : this is the Bragg peak.

Figure 2: Bragg Peak

Left : Slide from the Week 7 presentation, Right : Extract from the Week 7 Handout

Finally, I produced a translation of slides, handouts and videos in French for weeks 1, 4, 6 and 7. Since it is one of the main languages spoken at CERN, it made sense to extend the taught content to a wider community of students. Whilst the translation is still incomplete for the whole MOOC, it opens the possibility of further collaboration to further expand this project.

3 Conclusion

3.1 The Project

In this project, we set solid foundations for the publication of a MOOC aimed at undergraduate STEM university students. We provided the structure, lecture slides, handouts, first draft videos and a translation in French of the content. We are yet to film the lecture videos in a more professional environment with appropriate recording equipment, and the translation of the whole MOOC is not quite complete, but this opens the door to further collaboration to finish what we started.

We anticipate that the MOOC will be hosted online by a UK university, although no formal agreement has been reached yet. We hope that the course will become accessible during the first half of 2022, and it is expected to incorporate much of the content developed during this studentship.

I learnt a great number of things throughout this project - not only concerning antimatter or detector physics but more broadly on how to teach physics to non-physicists. Indeed, even though I had some previous experience in physics education, I certainly learnt a lot here about the best structure and approach to teach certain complicated topics.

I particularly enjoyed learning about plasma physics, which was a subject I hadn't been introduced to before, to talk about the difficulties of trapping antimatter. In fact, at the beginning of the project, I had doubts as to whether the target audience we chose (STEM undergraduate students but non-physicists) would help me learn anything whilst working on the MOOC - it turns out that the wide range of subjects covered by antimatter physics did bring me to discover new and interesting topics.

Overall, I really liked working on this quite special project. It certainly renewed an interest for physics education, and reinforces my determination to pursue further studies to become a researcher and lecturer at university. I take away the fact that antimatter is a much less niche and specialised topic than I thought it was, and that it covers a number of theoretical and experimental fields of physics. Talking about the frontier of antimatter research got me particularly excited about the biggest questions involving antimatter that we have concerning our universe.

3.2 My Experience

The CERN summer internship truly was an enriching experience. On an academic level, I learnt a lot through the lectures, which covered a wide array of topics; the project also taught me new things about antimatter and related disciplines that I found very much captivating. On a personal level, I particularly appreciated the social events, as exchanging with other students who share the same passion and interests is always great.

I also enjoyed the virtual visits, although as a feedback I would encourage the organisation of smaller groups of students instead of a whole cohort of 200 people being in the same zoom call. Of course, it is impossible to organise so many visits in small groups for this many students; but perhaps not making all the visits mandatory and just arranging a single visit per student amongst a small group of other students would have been more interesting.

I really found the lectures incredible - to be exposed to so many different topics at the frontier of human knowledge is incredibly exciting for me as an academic. I found the theoretical ones particularly suited for what I want to do in my professional life, that is, work as an academic in mathematical and theoretical physics; but a number of lectures on statistics and experimental methods were also captivating. The lecture "Antimatter in the Lab" by Chloe Malbrunot was also very useful for my project, and brought me a lot of resources and information on the frontier of antimatter research.

To conclude, I think this internship was an incredible experience for me as an individual as well as on a professional level. I had the chance to work on a really interesting physics education project on antimatter, I was lucky enough to interact and network with brilliant minds that will surely be the geniuses of tomorrow; overall, I am glad and thankful to have had such an amazing opportunity.

4 Acknowledgements

Special thanks to my supervisor Dr. Muhammed Sameed, whose guidance has been invaluable to the project. A big thank you also to Dr. Mark Andrew Johnson for his very helpful advice throughout this internship, and to Ahmed Al-Kharusi for his dedication and his hard work, with whom it has been a pleasure to collaborate. Finally, many thanks to the summer students' team for their assistance and their cheerfulness which is very much appreciated in these tough times, and to CERN more generally for providing such a unique opportunity.

5 Bibliography

Many resources were used during this project, many of them being pictures of experiments and diagrams of an apparatus or a technique, used in the lecture slides. These pictures were usually taken from the respective CERN experiments' website, giving appropriate credit when needed; although some resources were also taken from outside sources, usually license-free, with attribution explicitly given in the slides when needed.

We also mostly used information available on the websites of CERN experiments or of other collaborations. I also used a lot of content that I learnt in my particle physics lectures at university, and it felt very exciting to apply some of the theory taught in an academic context to a professional environment. I also used information from the CERN lectures of "Antimatter in the Lab" by Chloe Malbrunot, which were very instructive especially for the applications of antimatter where I had the opportunity to ask specific questions about them in the Q&A session. Two particularly interesting papers that we used a lot for our work on particle traps, detectors and plasma physics are

- Amole et. al., The ALPHA antihydrogen trapping apparatus. Nuclear Instruments and Methods in Physics Research A. October 2013.
- Fajans, Surko. Plasma and trap-based techniques for science with antimatter. Phys. Plasmas 27, 030601 (2020); doi: 10.1063/1.5131273.

We also provided our own diagrams, graphs and animations. Ahmed focused on creating great computer simulations for students to use, whilst I produced several graphs and diagrams, most notably in weeks 1 and 4. I also translated some of them in French for the French version of the MOOC when required.