Determining the amount of chaos in a particle physics experiment for an application in hadrontherapy

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I - Why do we want to come to CERN or DESY ?

We are the PAPI-ION team : **P**hysics **A**pprentices under **P**article physics **I**nvestigation with H^+ **ION**s. This team name refers to the butterfly effect ("effet **papillon**" in french) : indeed, we want to come to CERN or DESY to study chaos in particle physics !

The Beamline for Schools competition represents a real opportunity for young scientists like us to experiment with renowned searchers and science enthusiasts who will be able to teach us many notions about particle physics. As students who would like to become engineers or research workers, we think that carrying out this project and maybe going to the CERN will be very beneficial for our future studies and occupations. Moreover, we are aware that the LHC of the CERN is the largest, the most impressive and above all the most powerful particle accelerator of the world so we would be flattered to go there. This is the reason why our French team wants to apply for this contest. We are indeed exceedingly motivated to see our experiment grow in this research institute and finally going to one of the laboratories would be a way to rekindle the enthusiasm for science in our establishment which is one of our main goals.

II - Experiment proposal

This year, in our physics club, we were interested in chaos theory. Preparing the Beamline for Schools competition, we asked ourselves whether a particle physics experiment could be chaotic, and if so in what proportion?

Our proposal aims to determine the amount of chaos there is in a collision experiment of a protons or pions beam on graphite oxide. We chose this experiment because it represents a simplified model of a hadrontherapy experiment. We thus hope to be able to find results which would find a concrete application in the field of medicine.

Indeed, it seems important to us to know what part of chaotic phenomena there is in hadrontherapy. More specifically, how sensitive are experiments to the initial conditions ? This will allow us to know if this therapy can be generalized despite the diversity of patients and treatment conditions.

1) Our theoretical starting point : chaos theory in the well-known double pendulum experiment

To understand how to study chaos in a particle physics experiment, we have chosen to briefly analyse the example of the double pendulum, which is known for its chaotic character.
One of the characteristics of chaotic systems is that they exhibit sensitivity to initial conditions. This sensitivity is popularly known as the "butterfly effect".

The double pendulum consists of a single pendulum at the end of which a second single pendulum is attached. The assembly is then set in motion from a certain configuration, determined by the initial conditions. This system is known to be chaotic: the pendulum's motion will greatly differ even when the initial conditions are barely altered.

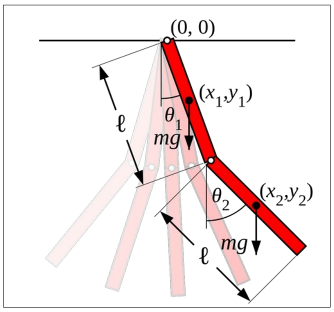

Fig n°1 : *Double compound pendulum. The angles θ_1 and θ_2 are 2 initial conditions.*

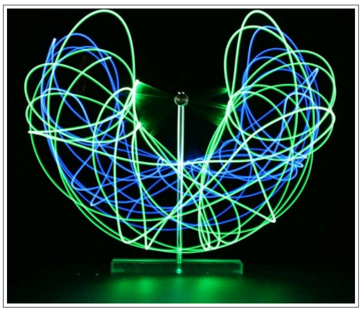

Fig n°2 : *Long exposure of double pendulum exhibiting chaotic motion*

It is possible to carry out a theoretical and numerical study of the double pendulum. By determining the acceleration vectors and applying Newton's second law, we can link the net force on each mass to its acceleration, considering the two-dimensional nature of the system. The positions are then obtained by integrating the acceleration and velocity functions.

To demonstrate the sensitivity of the double pendulum system to initial conditions, an appropriate graphical representation is required. This representation must show the divergence of the final parameters as a function of the initial parameters. Since it is impossible to simultaneously represent all of the four final parameters by showing their dependence on the four initial conditions, it is necessary to restrict to a representation of each parameter separately according to a subset initial parameters. A two-dimensional representation makes it possible to represent a final parameter as a function of two initial conditions varying in two given intervals.

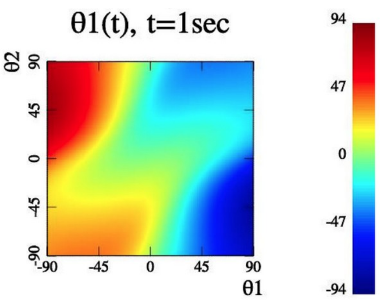

Fig n°3 : *2D diagram. Values of the variable θ_1 at time t=1s depending on the initial values of θ_1 and θ_2.*

We can thus, thanks to the graph, observe the sensitivity to the initial conditions of the double pendulum system. The more contrasted the diagram, the more chaotic the system.
We wish to draw inspiration from this mode of representation to evaluate the proportion of chaos in a particle physics experiment.

2) Experimental setup

We chose to study the chaos in the experiment of the 2018 winning team *beamcats*. In this proposal, the skin tissue is emulated by graphite oxide to understand, to a greater extent, the effects that hadron beam therapy has on human tissue. Our choice of experiment is focused on this simplified hadrontherapy since we can easily vary the parameters of the experiment. This will allow us to concretely represent the impact of the variation, even tiny, of the initial parameters on output results. Here is the diagram of this experiment :

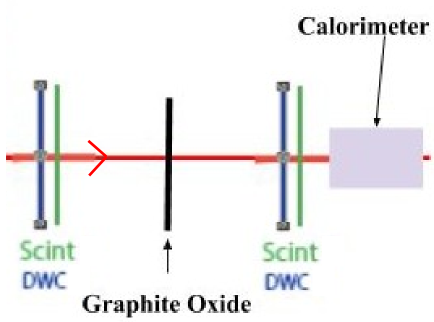

Fig n°4 : *Experimental setup diagram.*

This experiment adapts perfectly to our desire to measure the chaotic nature since it only depends on three distinct variables which are:

- the thickness of the graphite oxide target
- the angle of incidence of the beam
- the initial energy of the beam

To measure the observables of this experiment we will have available various instruments presented in the diagram such as the Delay Wire Chamber and the calorimeter.
Concerning the output data, we will be monitoring the energy of the particles passing through the graphite oxide using the calorimeter. We will also be looking at the distribution of the scattered particles with the output Delay Wire Chamber. We can, for example, use 2D dispersion indicators for our numerical analysis.

3) Experimental protocol

Our experiment will be carried out in three stages to try to characterize the chaotic degree of hadrontherapy :
After having carried out the first measurements which will serve as a reference sample. We will first rotate the target to adjust the beam incidence angle. We will also modify the incident energy of the beam and use different targets to modify the thickness of the graphite oxide. We will not limit ourselves to varying these parameters one after the other, but we will seek to combine them to obtain the most complete results possible.
Once these values have been acquired, we will list them in different graphs. For example, we can plot a graph in which each point corresponds to a beam with a given initial energy and a given incident angle. They are respectively the ordinate and abscissa components of this point. In addition, each point is associated with a color corresponding to the value of its final

energy (or the value of the DWC dispersion indicator). ***Fig n°5*** is an example of what kind of graph we can generate. Thanks to this modeling, we'll be able to conclude the chaotic nature (or not) of our experiment.

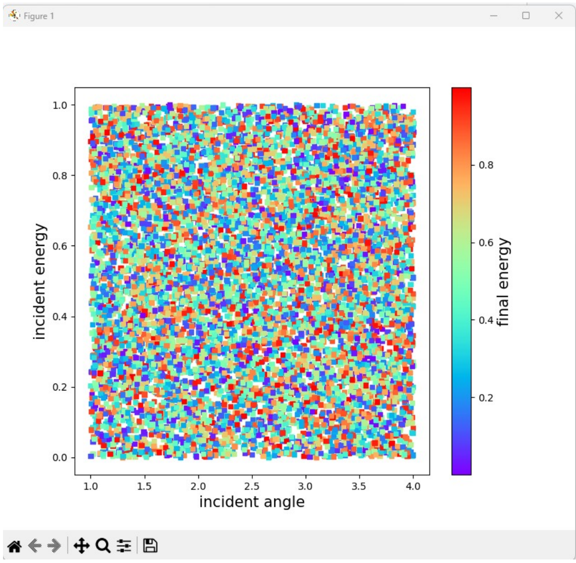

Fig n°5 : *result of a simulation with 10 000 random points (code in appendix).*

As an extension and with the help of researchers, we can also perhaps use the Lyapunov exponent, which quantifies the sensitivity of a physical system to initial conditions. Our experience can perhaps also be used to study the sensitivity of detectors. So many ideas that we would like to explore...

III - What we hope to take away

This project allowed us to take an interest in a new approach to physics, which is not covered in our traditional school programs. It could also help us to develop our scientific mind and our reflection on the smallest aspect of the world, which is barely taught in our school.
This group work was interesting and permitted us to develop and gain skills and abilities. According to all of us, this experience was truly one of the most enriching ones we have had due to the high number of interesting facts we knew nothing about beforehand. Our group cohesion has also been encouraging and created a great atmosphere to work and improve our mutual assistance and our confidence.
Therefore, we are hoping to be able to conduct our experiment in one of the laboratories to test the theory of chaos. We all have faith in the interesting information that the field of medicine could get from the chaotic attitude of particles.

IV - Acknowledgements

First of all, we'd like to thank CERN, particularly the BL4S project team, Margherita Boselli and Markus Joos, for their discussions, presentations, and answers to our questions.

Our thanks also go to Mr. Arnaud Gniady, our dear math teacher, and at partial time, talented personal physicist. He suggested us to enter the contest, created the team, carried the project, and gave us a lot of his time in order to allow us to grow the PAPI-ION team’s ideas.

V - Appendix

Code to plot the data :

```
import matplotlib.pyplot as plt
import matplotlib

x=[]    #incident angle values
y=[]    #incident energy values
e=[]    #final energy values

plt.figure(figsize=(8,7))
plt.xlabel("incident angle", size=15), plt.ylabel("incident energy", size=15)
plt.scatter(x,y,20,e,"s",cmap="rainbow")

plt.clim(min(e),max(e))
cbar = plt.colorbar()
cbar.set_label(label="final energy", size=15)
plt.show()
```