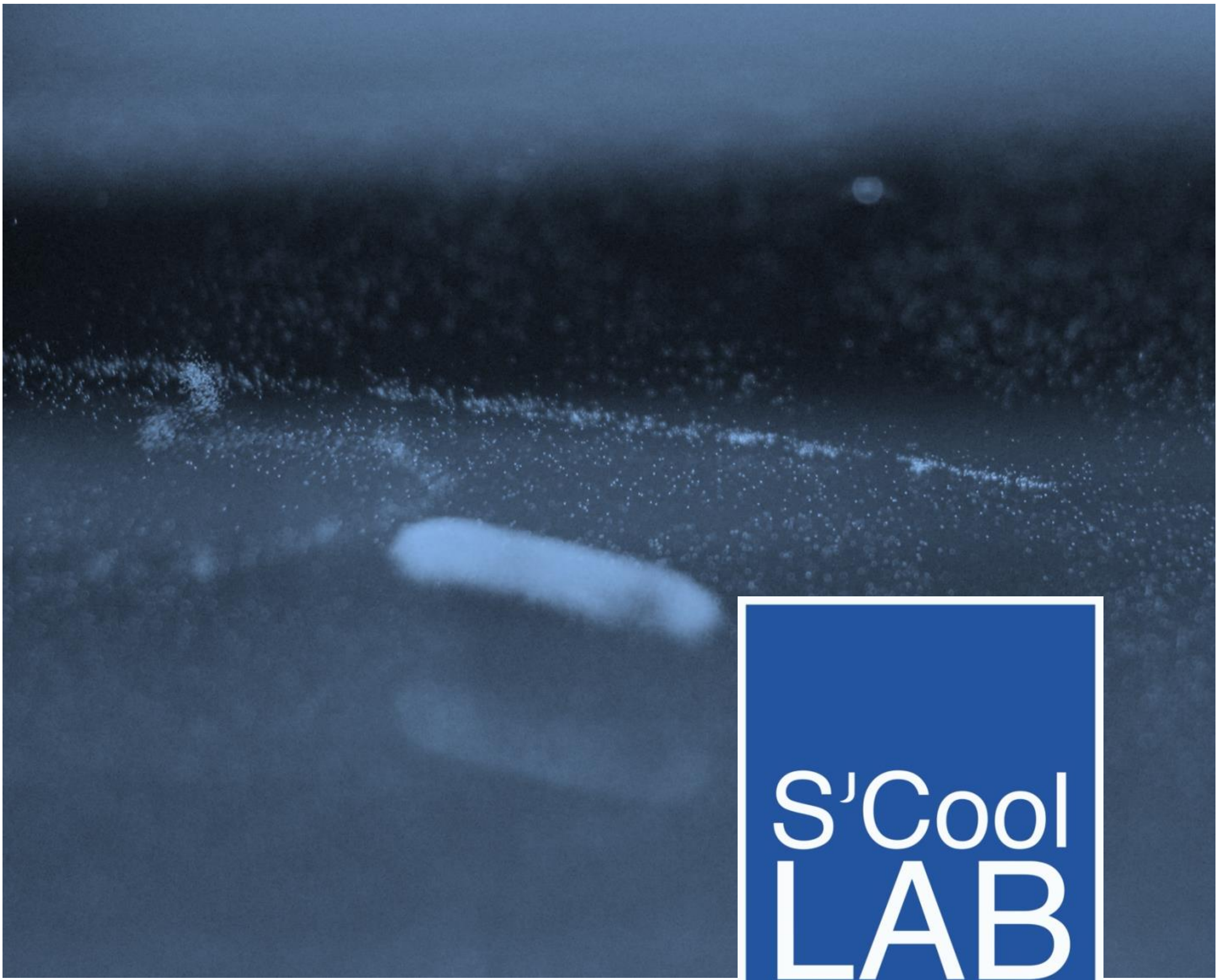


S'Cool LAB

Cloud Chamber

Do-it-yourself manual

Julia.Woithe@cern.ch S'Cool LAB

Contents

Woithe, J. (2016). CLOUD CHAMBER. S'Cool LAB - Do-it-yourself manual. Version 7

Brought to you by the S'Cool LAB team
http://cern.ch/s-cool-lab

More ideas for the classroom:
http://cern.ch/s-cool-lab/classroom-activities

1. Introduction: Build your own particle detector!

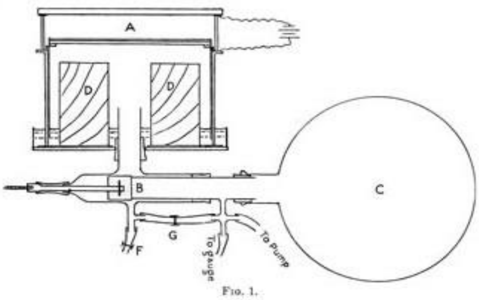
Particles coming from the universe are crossing the Earth all the time – they are harmless but invisible to us. Cloud Chambers are detectors which make the tracks of these particles visible. Some decades ago, these detectors were used in the first particle physics experiments. The following instructions will help you to build your own Cloud Chamber at home.

2. History of Cloud Chambers

The cloud chamber is one of the oldest particle detectors, and it led to a number of discoveries in the history of particle physics. It also was involved in two Nobel prizes!

Charles T. R. Wilson (1869 - 1959)

This Scottish physicist actually wanted to study cloud formation and optical phenomena in moist air. He discovered soon, that by accident he had invented a particle detector. He perfected the first (expansion) cloud chamber in 1911 and received a Nobel Prize in 1927.

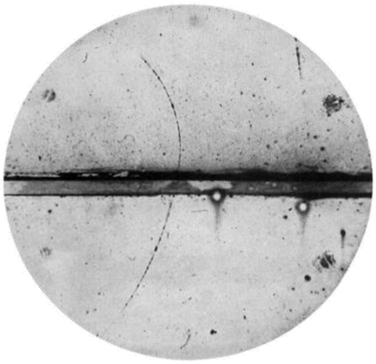


A diagram of Wilson's apparatus. The cylindrical cloud chamber ('A') is 16.5cm across by 3.4cm deep.

(Wilson, 1912)

Carl Anderson (1905 - 1991)

This American physicist discovered the positron in 1932 and the muon in 1936 using an expansion cloud chamber. He received a Nobel Prize in 1936. Anderson used alcohol instead of water to form a more sensitive mist and he applied a strong magnetic field to his chamber.

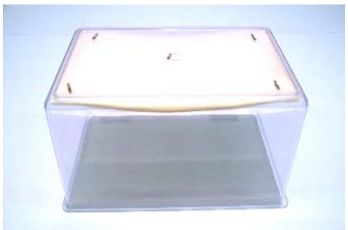


(Anderson, 1933)

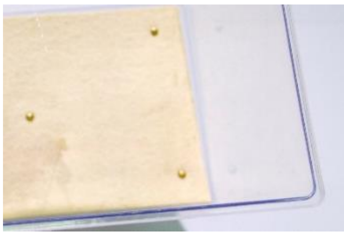
Timeline: Understanding Cosmic Particles

Read more about the exciting history of cosmic particles. Many of the historic experiments (discharge of electroscope, coincidence technique using Geiger counters, ...) can be set up in schools. Have a look at Bonolis (2011) or http://timeline.web.cern.ch/timelines/Cosmic-rays

3. SHOPPING LIST – PART 1



Plastic Container
clear, see-through box-like plastic container
with an open top, roughly 20 x 30 x 15cm
S'Cool LAB version: Ferplast container GEO extra large 11 l 35x23x22cm
Alternatives: any plastic box, or glass aquarium, …



Felt
a thick felt (few mm) to be attached to the bottom of the plastic box
S'Cool LAB version: 5 mm thick white felt
Alternatives: sponge, single use paper towels, …

Split Pins
to attach the felt to the inside of the bottom of the box
Alternatives: cable ties, wire, magnets, …

Box
a box that is just a little bit larger than the metal plate will contain the dry ice plates and the metal plate, the sides should not be much higher than 5cm, otherwise they will block the view
S'Cool LAB version: Plastic box "Allzweck-Behälter AZB01" isolated inside with 5 cm Styrofoam at the bottom and foam rubber at the sides, or CNC drilled foam case based on a new design: https://a360.co/3dfUuEl
Alternatives: Cardboard, styrofoam or wooden boxes, …

Metal Plate
to be placed on top of the dry ice (good heat conductivity is important)
to cover the open side of the container completely, needs to be black and could have little grooves matching the side walls of the plastic box (for isolation of the air volume inside)
S'Cool LAB version: anodised aluminium plate (d = 5 mm) with CNC milled groove based on the 3D design file: https://a360.co/2z3jiQN
Alternatives: Baking tray, frying pan, book holder, metal plate covered with black electrical tape (attention: very pure alcohol and very cold temperature are difficult conditions for most paint, you might need to repaint the plate after every use in this case)

3. Shopping list 2

Light Source

a very intense, bundled light source

S'Cool LAB: HOLEX LED rechargeable rod lamp 260 mm

Alternatives: overhead projector, LED strip, battery charged lamps …

Protective Equipment

to handle isopropanol and dry Ice it is necessary to wear personal protective equipment

- safety goggles (for dry ice and Isopropanol)
- nitril protection gloves (for Isopropanol)
- leather protection gloves (for dry ice)

Dry Ice

Solid carbon dioxide at -78°C

Read the safety instructions!!!

touching it directly will cause burns, evaporating dry ice will enrich the air with carbon dioxide, **only use in well ventilated rooms**

dry ice in airtight containers will build up high pressure

Where to buy:

- google "dry ice online shop"
- have a look at www.dryicedirectory.com

Other sources: Universities (chemistry institutes), fish processing, dry ice cleaning, …

Isopropanol / Isopropyl alcohol

Pure (>90%) isopropyl alcohol

Read the safety instructions!!!

Keep away from children

never drink it, handle with gloves and goggles

Where to buy:

drug store (e.g. as "Alcohol First Aid Antiseptic")

4. Step by step instructions

1. Prepare the metal base plate

If you were not able to get a black metal plate, wrap one side of a metal plate completely with black electrical tape. This will make it much easier for you to see the “white particle tracks” later on in front of a black background. The bottom will be in contact with alcohol when you run the chamber, so do not use alcohol-soluble tape or glue to attach it. Alternatively you can use black nail polish or spray paint. If you have already a black metal plate you can skip this point.

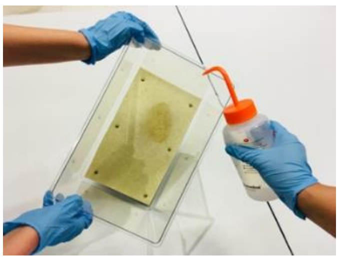
2. Prepare the alcohol dispensing felt

Drill small holes carefully in the bottom of your plastic container, e.g. aquarium. Attach the felt with the split pins to the bottom of the box. Later on this felt will be soaked with alcohol and will produce a rain-like mist of alcohol. Don’t use glue – the alcohol will solve it fast.

3. Assembly of the Cloud Chamber

Put on leather gloves and safety goggles.
Cover the bottom of your box with dry ice.

Next you will add the Isopropanol to the chamber. Make sure you wear plastic gloves and safety goggles. Again – never drink the alcohol and keep it away from children! It is very crucial that you use the right alcohol – the chamber will not work with another one.



Soak the felt with Isopropanol. This Isopropanol will later form the mist in which you see the tracks appearing. Tilt the chamber when you fill in the Isopropanol. You will see when the felt is completely soaked once there is a little “lake of Isopropanol” in one corner. You can use the remaining alcohol later to fill the groove of the metal plate.

Place your black metal plate onto the dry ice. Make sure you have already soaked the felt inside the plastic container! If your plate becomes cold, the water vapour in the air will condensate/freeze on it and form a white “snow layer” after a few minutes. Since you need a black surface for contrast reasons, you would have to clean the plate in this case.

Use Isopropanol to fill the groove of your metal plate - if you have it. This will help sealing the box.

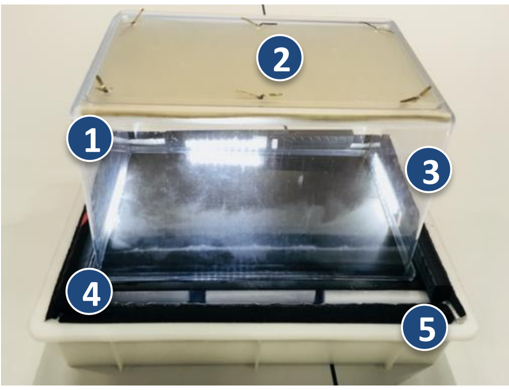
Place your plastic container upside down onto your metal plate. Fit the box so that the box walls fit the grooves in the metal plate. Now your chamber is ready to detect particles. It will only take a few minutes until everything has cooled down and a stable sensitive area has formed.

At first, you will only see a rain-like mist of alcohol. Place your torch lights in a way, that they illuminate the alcohol mist right above the metal plate – that is the sensitive area of the chamber.

Turn off the room lights and turn on your torches. After a few minutes, you should start seeing tracks of high-energy particles passing through. The tracks look a little like spider's threads going along the chamber floor. You should be able to see approx. one track per second. If needed, you can add extra alcohol through the holes in the top of the box without reopening the box.

4. How does the Cloud Chamber work?

At the top of the box, Isopropanol evaporates from the felt (i.e. exists in gaseous form) and slowly sinks down towards the metal plate, because Isopropanol vapour is heavier than air. The dry ice keeps the bottom very cold, therefore the isopropanol cools down rapidly when falling. The result is a so called supersaturated environment. This means, the alcohol is in gaseous state, but at a temperature at which isopropanol vapour normally can't exist. Therefore, it will very easily condense into a liquid state if anything disturbs its equilibrium. Now what happens if an electrically charged particle crosses the chamber? The particle will *ionize* the vapour: it tears away the electrons in some of the gas molecules along its path. This leaves these molecules electrically positively charged. This is enough to start the condensation process: Small droplets of alcohol form along the path of the initial particle through the chamber. The ordered accumulation of these droplets are the tracks you see appearing.[1]



1 See-through box

2 Felt

3 Torch light

4 Black metal plate

5 Box with dry ice

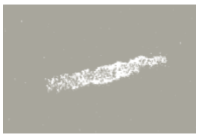
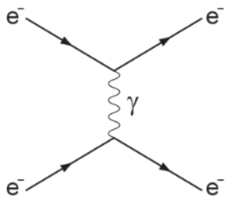
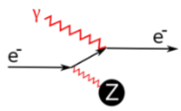
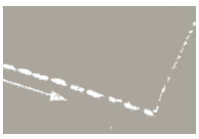
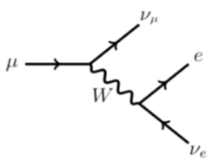
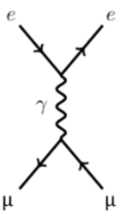
What are cosmic particles?

Different types of particles come from stars, galaxies and other sources in the universe. For example, protons, helium nuclei and electrons travel through the universe all the time, as well as neutrinos and photons. These particles are also called cosmic particles. Their energy ranges from about 10^9 electron volts (eV) to about 10^{20} eV. For comparison: The currently largest particle accelerator LHC at CERN, accelerates protons only to a ten million times lower energy (maximum 10^{13} eV). Have a look at the table on page 14 of this booklet for more information about cosmic particles.

[1] Look up (Nuffield Foundation, 2016) for more information about this process.

5. What can you see?

You will see different kinds of tracks, which differ in length, thickness and shape and are produced by different types of particles.

Pictures © Karlsruher Institut für Technologie (KIT)	**Particle**	**Explanation**
	**muon or anti-muon**	Thin straight tracks - fast particles with high kinetic energy - they ionise molecules without scattering - high energy muons, electrons or their corresponding anti-particles - source: secondary cosmic particles
	**electron or positron**	
	**α particle system**	Thick straight tracks (approx. 5 cm): - alpha particle systems (2p2n) - massive particle systems with high “ionisation density” (for alpha: 1 MeV/cm) - source: Radon-222 gas, natural radiation
	**electron** 	Curly / curved tracks: - slow electrons scatter with other electrons via electromagnetic interaction - the lower the momentum of a particle, the easier it scatters - Photoelectrons are low energy electrons set free by high energy photons (via Photoelectric effect) - Source: muon transformation, beta emitters, photoelectric effect
	**photoelectron** 	
	**muon transformation** 	Kinks: This could be a muon (or anti-muon) transforming into an electron (or positron), a neutrino and an anti-neutrino.
Y	**electron-muon- scattering** 	Y-shape: This could be a muon knocking off an electron (bound to an atom) via electromagnetic scattering.

6. Troubleshooting and FAQ

Although cloud chambers are a very reliable research tool, things might not work from the beginning and you might encounter some of the following challenges or questions.

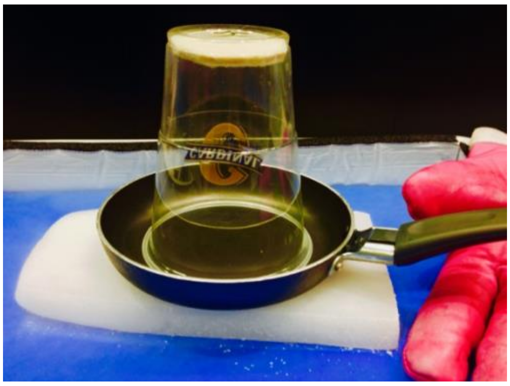
Challenge / Question	Solution
"I don't see any tracks!".	Vary the position of your light source – make sure that the sensitive layer of the detector (approx. 1 cm above the metal plate) is well illuminated. Make sure the dry ice is in good contact with the metal plate. If the dry ice is rather old, scrape off the surface layer of the ice blocks to get rid of water ice which freezes onto the dry ice. Add more isopropanol to make sure the chamber is well saturated. Check that the chamber is airtight; you can use tape or plasticine to seal it.
"I only see mist, and no tracks."	Wait. It takes approx. 5 minutes for the chamber to get to the right temperature. Make sure that you use the right alcohol – other alcohol have different "activation energies" that so that cosmic rays will not be able to start the condensation process.
"I see big clouds at the edges of the chamber."	This probably means you have an air leak. Make sure that the chamber is tightly sealed.
"I can't see tracks because the black metal plate has a cover of snow."	This sometimes happens, if the metal plate is exposed to normal air and dry ice at the same time: The water vapour from the air freezes onto the metal plates procuring a white icing. Start again; make sure to close the chamber as soon as possible e.g. by preparing the felt with isopropanol before you place the metal plate on top of the dry ice.
"I have read that some cloud chambers use high electric fields. Why?"	A strong electric field (approx. 100 V/cm) is often used for professional cloud chambers to pull ion tracks down to the sensitive region of the chamber. As ionising particles pass above the sensitive area of the chamber, they leave an ion trail behind but no condensation start. When pulled down to the supersaturated layer, condensation around the ions starts and droplets can be observed.
"I have learned that magnets deflect electrically charged particles but my fridge magnet has no effect."	To see the curvature of high-energy particles in a magnetic field with your bare eye, you need very strong magnetic field of several Tesla. For example: the bending radius of a high-energy electron ($m_e = 0{,}51 \frac{MeV}{c^2}$) with $E = 1\ GeV$ in a magnetic field of $B = 2\ T$ is $1.7\ m$! $$E = \sqrt{m_e^2 \cdot c^4 + p^2 \cdot c^2} \approx p \cdot c\ (for\ m \ll p, highly\ relativistic\ particles)$$ $$p \cdot c = e \cdot r \cdot B \cdot c \Leftrightarrow r = \frac{E}{e \cdot B \cdot c} = 1.7\ m$$
"What is the squeaking sound when I put the metal plate on top of the dry ice?"	When the metal plate is placed on the dry ice, a strange loud noise is produced. This happens because the dry ice sublimates instantly upon contact with the warm metal plate. The gas bubbles burst because of the pressure by the metal plate – that is causing the noise.

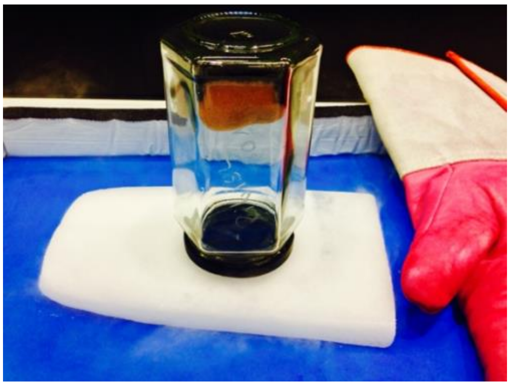
7. More about cloud chambers

Alternative setups
There are many different versions of cloud chambers you can find on Youtube or in Education Journals. Here some examples:

- Fish Tank Cloud Chamber (Green, 2012)
- Cloud Chamber build with gel ice packs instead of dry ice (Kubota & Kamata, 2012)
- Cloud Chamber build with a water ice / salt mixture (Yoshinaga, Kubota, & Kamata, 2014)
- Cloud Chamber build with liquid nitrogen (Zeze, Itoh, Oyama, & Takahashi, 2012)

Our favourites:


“Frying-Pan-Chamber”


“Cloud-in-a-Jar” (Nova, 2015)

“Modern” Cloud Chamber at CERN: CLOUD experiment
Learn about clouds and the climate and why CERN is investigating cloud formation (Kirby, Richer, & Comes, 2016).

Hiking with cloud chambers
What happens to a cloud chamber in 4300 meters height? Carl Anderson took a cloud chamber to Pike’s Peak in 1936 (Anderson & Neddermeyer, 1936).

8. Additional Information / Ideas

Test of special relativity

Most of the tracks you see in the cloud chamber are caused by muons. Muons have similar properties than electrons but are much (approx. 200 times) heavier and therefore are not stable but have a really short mean lifetime of 2.2 µs. They transform into an electron and two neutrinos. This actually provides an interesting test of special relativity: muons are typically produced around 15 km up in the atmosphere, when cosmic particles interact with the atmosphere and thereby transform into lighter particles. To reach the surface of the earth, muons at the speed of light would need 50 µs - over 20 muon lifetimes! Thus we would expect only very few muons to make it. However, when applying Einstein's rules of special relativity to the very fast muons, time in the their frame of reference is significantly dilated as seen by an observer on Earth, meaning that a significant fraction can, in fact, make it to the surface. On average, 1 muon passes through the palm of your hand every second with an energy of typically 1 GeV to 1 TeV.

Radioactive Sources

In addition to cosmic particles, radioactive sources can be used in cloud chambers. Be aware that you will see less cosmic particle once a radioactive source is present in the chamber. We recommend to study first only secondary cosmic particles, because it is amazing how many tracks you can see (and that's just natural radiation). If your chamber is very small or simply not working very well – or if you have seen cosmic particles already – then use the sources. A nice tool to find out about half-lives, alpha energies, daughter nuclei and decay chains: "IAEA Isotope Browser App" (Android and iOS).

Thoriated welding rods

Thorium oxide has been used for many years in tungsten welding rods having been found effective in terms of long life and thermal efficiency. These welding rods can be purchased in various online shops. Look for "2% Thoriated Tungsten electrodes, colour coded Red" or "WT 40 Schweißdraht" (approx. 30€ for 10 Pieces). The alpha decays and beta transformation in the Th-232 decay chain lead to nice tracks in a cloud chamber. Cover the welding rod in paper too show shielding of alpha particles!

Radon & daughter nuclei from the air

Bastos, Boff, & Melquiades (2016) show how to make use of the radioactive isotopes in the air in the physics classroom. Very interesting: Electrically charges balloons collect radioactive isotopes attached to dust particles from the air within a few minutes (Austen & Brouwer, 1997). Our recommendation: Blow up a balloon, charge it via friction (use cat fur or your hair), attach the balloon to a wall, wait 10-20 min. Then destroy the balloon carefully and put it inside a cloud chamber. After the chamber has cooled down again you will see many alpha tracks originating from the balloon.

Other detectors

In addition to cloud chambers, other types of detectors can be used to learn more about cosmic particles.

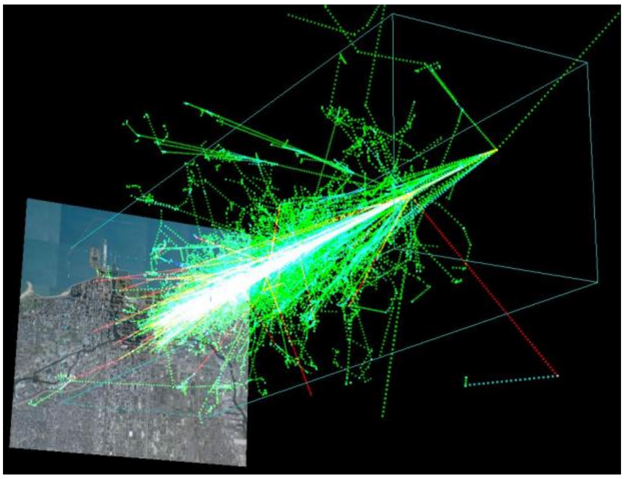
- **Muon Hunter Project**
  Build your own muon telescope (2 Geiger counter in coincidence, connected to Rasberry Pi). Allows to measure muons and e.g. their angular distribution http://www.muonhunter.com (approx. 150 €)

- **Pixel detector**
  Portable Small USB Camera "MiniPIX" by ADVACAM: pixelated 300 µm Silicon detector chip (256 x 256 pixels, 55 µm pitch) which allows online detection, visualization and analysis of single ionising particles http://advacam.com/camera/minipix (several thousand Euros)

Air showers

High-energy cosmic particles create a cascade of billions of new particles (so-called air shower) when they interact with the atmosphere. Scientists study these air showers to learn more about the energy and origin of high-energy cosmic particles. The Pierre Auger Observatory is one example for an international cosmic particle observatory with a detection area of 3000 km^2.

Air shower simulation
You can find different simulations of air showers online, for example:
AIRES Cosmic Ray Showers http://astro.uchicago.edu/cosmus/projects/aires/
In the picture below, different kinds of particles are coloured differently (here: electrons & positrons green, muons red, and gamma rays cyan).



Research about air showers & public data
More information about the Pierre Auger Observatory can be found online, for example here:
http://auger.org/education/Auger_Education (website is quite old)
A public event display with real data from air showers recorded by the Pierre Auger Observatory:
https://www.auger.org/index.php/edu-outreach/event-display

9. ACKNOWLEDGEMENTS

The cloud chamber has a long and interesting history in particle physics research. Almost as long is the history of using cloud chambers for educational purposes. While the first cloud chambers were pulsed expansion chambers, Langsdorf (1939) first proposed a continuously sensitive diffusion cloud chamber based on a refrigerating system and methanol vapour. Cowan (1950) first proposed to use dry ice to cool down the anodized aluminium plate at the bottom of a diffusion cloud chamber. He already used this setup for demonstration purposes and foresaw the huge educational value of his apparatus “which is ideally suited for classroom use, for individual use, or even as a scientific toy” (Cowan, 1954).

The design of the S’Cool LAB cloud chamber setup is based on Andrew Foland at Cornell, who documented the first “kitchen-table-cloud chamber" in the late nineties. Brought to CERN by Silvia Schuh-Erhard, the setup was shown during the Open Days at CERN in 2004 after receiving major fine tuning by Dominique Bertola. Since 2005, DIY cloud chamber workshops are a key component of CERN’s teacher programmes, and since 2014, part of S’Cool LAB’s equipment. We hope, that also future generations of young scientists will be inspired when watching the tracks of cosmic particle in a hand-made cloud chamber!

10. BIBLIOGRAPHY

- Anderson, C. D. (1933): The Positive Electron. Physical Review 43, 491–494.doi:10.1103/PhysRev.43.491
- Anderson, C. D., & Neddermeyer, S. H. (1936). Cloud chamber observations of cosmic rays at 4300 meters elevation and near sea-level. Physical Review, 50 (4), 263-271.
- Austen, D., & Brouwer, W. (1997). Radioactive balloons: experiments on radon concentration in schools or homes. *Physics Education*, *32*(2), 97.
- **Bastos, R. O., Boff, C. A., & Melquiades, F. L. (2016). Nuclear physics experiments with low cost instrumentation. *Physics Education*, *51*(6), 065013.**
- **Bonolis, L. (2011). Walther Bothe and Bruno Rossi: The birth and development of coincidence methods in cosmic-ray physics. *American Journal of Physics*, *79*(11), 1133-1150. arXiv:1106.1365 [physics.hist-ph]**
- Cowan, E. W. (1950). Continuously sensitive diffusion cloud chambers. Review of Scientific Instruments, 21(12), 991-996. http://aip.scitation.org/doi/pdf/10.1063/1.1745504
- Cowan, E. W. (1954) Cloud chamber. U.S. Patent 2,676,266, issued April 20, 1954.
- **Drescher, H.-J. Cosmic Ray Air Shower Pictures** http://fias.uni-frankfurt.de/~drescher/CASSIM/
- Foland, A. How to Build a Cloud Chamber http://njsas.org/projects/atoms/cloud_chamber/cache/cloud.html
- Green, F. (2012). Making a fish tank cloud chamber. Physics Education, 47, 338-341.
- **Kirby, J., Richer, C., & Comes, I. (2016). Cloudy climate change: How clouds affect Earth's temperature - Jasper Kirkby . From TEDEd Lessons Worth Sharing:** http://ed.ted.com/lessons/cloudy-climate-change-how-clouds-affect-earth-s-temperature-jasper-kirkby
- Kubota, M., & Kamata, M. (2012). Simple cloud chambers using gel ice packs. Physics Education, 47, 429-433.
- Langsdorf, A. (1939). A continuously sensitive diffusion cloud chamber. Review of Scientific Instruments, 10(3), 91-103. http://hep.ucsb.edu/people/hnn/cloud/articles/ALangsdorfRSI10_91_1939.pdf
- Nuffield Foundation. (2016). Alpha Particle Tracks. From Practical Physics: http://practicalphysics.org/alpha-particle-tracks.html
- **Nova (2015): How to Reveal Subatomic Particles at Home**. www.youtube.com/watch?v=wN_DMMQEhfQ
- **Particle Data Group (2016). The Review of Particle Physics. Chapter 29: Cosmic Rays. Chin. Phys. C, 40,** http://pdg.lbl.gov/2016/reviews/rpp2016-rev-cosmic-rays.pdf
- Wilson, C. T. R. (1912). On an Expansion Apparatus for Making Visible the Tracks of Ionising Particles in Gases and Some Results Obtained by Its Use. Proc. R. Soc. Lond. A. 87, 277-292. doi:10.1098/rspa.1912.0081
- Yoshinaga, K., Kubota, M., & Kamata, M. (2014). Simple cloud chambers using a freezing mixture of ice and cooking salt. Physics Education, 50, 23-27.
- Zeze, S., Itoh, A., Oyama, A., & Takahashi, H. (2012). A sensitive cloud chamber without radioactive sources. Physics Education, 47, 574-578.

11. More information about cosmic particles...

<table>
<tr><th></th><th>Primary cosmic particles</th><th>Secondary cosmic particles</th><th>Solar particles</th></tr>
<tr><td>Origin</td><td>Space (supernovae and other astrophysical sources)</td><td>produced in interaction of primary cosmic particles with interstellar gas or the atmosphere of the Earth</td><td>Sun
(sun wind, solar flares, coronal mass ejections)</td></tr>
<tr><td>Composition and energy</td><td>stable high-energy, electrically charged particles and nuclei:

79% protons
17% helium nuclei
3% heavier nuclei
1% electrons
<1% positrons and antiprotons

$E \approx 100\ MeV - 10^{20}\ eV$

Isotropic = particles come from all directions</td><td>at sea level:
muons, anti-muons (70%)
▪ most numerous charged particles at sea level, produced typically high in the atmosphere (15 km)
▪ energy loss in atmosphere: 2 GeV
▪ mean energy at sea level: 4 GeV
▪ Intensity $I \approx 1\ cm^{-2}\ min^{-1}$
▪ 1.3x more anti-muons than muons (more protons than neutrons in primary cosmic radiation)
electrons, positrons, photons (30%)
▪ from transformation processes in the atmosphere
▪ primary source for low-energy electrons: muon transformation</td><td>sun wind: very low energy protons $E < 1\ keV$
solar flares and coronal mass ejections (CME): higher energy protons $E \approx 10\ MeV$ ≈ 1-6 events per day
solar energetic particles (SEP): high-energy protons E up to $1\ GeV$ ≈ 1 event per year</td></tr>
<tr><td>Fun facts</td><td>Oh-My-God particle: highest-energy cosmic particle detected to date (1991, Utah): $E = 3 \cdot 10^{20}\ eV$</td><td>High-energy muons are able to penetrate hundreds of meters of matter: 10 MeV muons penetrate 6 km water. A shower of millions of secondary cosmic particles can be caused by a single high-energy cosmic particle ($E > 100\ TeV$), see air shower simulation by Drescher</td><td>How do we know, that the particles we see in the cloud chamber don't come from the sun? Compare the chamber at day and night (or during a solar eclipse) like Victor Franz Hess 1912.</td></tr>
<tr><td>Magnetosphe</td><td colspan="3">The flux of lower energy (<10 GeV) cosmic particles depends on the solar activity and the Earth's magnetic field: particles are decelerated and partially prevented from reaching the Earth's atmosphere. Electrically charged particles are also trapped in the Van Allen radiation belt (outer belt: 100 keV - 5 MeV electrons, inner belt: 100 MeV-1 GeV protons). Nice side effect of disturbances in the magnetosphere caused by sun wind: Auroras. East-West anisotropy: Low energy primary protons from the east are suppressed compared to those from the west, because of the Earth's magnetic field. This also affects the secondary cosmic particles.</td></tr>
<tr><td>Important for us</td><td>▪ Atmospheric chemistry (ionization causes ozone depletion, cosmogenic radioisotopes e.g. C-14)
▪ Possible effect on climate change (see CLOUD experiment at CERN)
▪ Radiation dose needs to be considered for human space flight
▪ Produce secondary particles when they interact with the atmosphere</td><td>▪ Contribute to annual radiation exposure (approx. 0.4 mSv)
▪ Might have an effect on evolution (mutation rate)
▪ Can cause electronics problems at sea level
▪ By measuring secondary cosmic particles we only measure the remnants of the primary particles. To find out more about the primary particles, we need to measure outside the atmosphere e.g. with the AMS detector, which is attached to the ISS.</td><td>High particle flux, but at lower energies. Magnetic field and atmosphere shield us from most effects, but:
▪ Outside the atmosphere: can cause problems with electronics (cosmic particles have enough energy to change the states of circuit components, e.g. data in electronic memory devices)
▪ Need to be considered for human space flight</td></tr>
</table>

Your observations:

Your notes: