Visualizing traces of ionizing radiation using a homemade Wilson-like cloud chamber

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In a first part the cloud chamber developed by Charles Wilson is presented. The main characteristics of this device, which aims at detecting and visualizing ionizing radiations, are reviewed. A variation of the Wilson chamber devised by Alexander Langsdorf, called the diffusion cloud chamber, is also described. The latter is nowadays largely exploited to build homemade or commercial imaging detectors to show the traces of subatomic particles. Finally the construction and the operation of our homemade cloud chambers are explained.

Introduction

It is difficult for anyone to form an enlightened opinion on such an important social issue as nuclear energy. For secondary school students it is hard to learn about nuclear, particle or cosmic ray physics because we cannot see or feel ionizing objects such as alpha, beta, gamma radiations or muon, pion particles. Nevertheless, it could help and maybe attract interest into the subatomic world by showing that natural radiations exist by using a simple device like a homemade cloud chamber. This makes it easier to answer questions such as "What is radioactivity?", "Why are some objects slightly radioactive?" or "What are the effects of ionising radiation passing through matter?". And this device clearly shows that radioactivity is everywhere in Nature and has always been part of our daily life.

Cloud chambers are ideal instruments for showing ionising radiation live and thus for convincing people that these are real physical objects with measurable properties; they allow demonstrating that these ionizing particles can be detected via an interaction with a sensitive medium, a mixture of a gas and a condensable vapour to be precise, through which they leave a trail of their passage like an aeroplane leaves a track of its passage in a bright sky.

After a brief history, we will describe the operation principle of the cloud chambers, differentiating between the two types of operation: expansion and diffusion types. An overview of the major discoveries in particle physics achieved with these detectors will be given. We will then focus on our homemade cloud chamber prototypes based on the diffusion-type cloud chamber. We will give practical details on the construction and operation steps. Finally, we will present pictures of interesting events obtained when our chambers were used with cosmic rays or with ionising radiation emitted by slightly radioactive objects.

The Wilson Cloud Chamber and its Successor

Charles Wilson was a Scottish physicist studying cloud formation and related optical phenomena like the Brocken spectre [1] observed typically when looking from mountaintops into fog with the sun behind the observer. In 1894, in order to reproduce these effects in Cavendish laboratory, C. Wilson developed a device consisting of a closed container filled with a mixture of air and water vapour and fitted with a piston. A sudden expansion movement of the piston cooled the mixture so that air became supersaturated with vapour; moisture can then condense on dust particles as already studied by the meteorologist Dr John Aitken [2]. C. Wilson perceived that charged ions could also act as condensation centers in such devices. This led in 1911 to the construction of his cloud chamber based on a transparent cylinder 16.5 cm in diameter and 3.4 cm high as a detection device [3]. Charles T. R. Wilson was awarded a Nobel Prize in 1927[1] for this invention, more exactly for "his method of making the paths of electrically charged particles visible by condensation of vapour" [4].

Cloud chambers along with bubble chambers developed by Donald A. Glaser[2] in 1952 [5] are based on a similar principle of operation. A sudden release of the pressure leads to a metastable equilibrium of their sensitive medium. The supersaturated gas or the superheated liquid, respectively for cloud or bubble chambers is disturbed by the ionization track left by the charged particle passing through them. The change of state forms droplets or bubbles which, when properly illuminated, reveals the radiation trails. Photographs taken by separate cameras at different angles made it possible to reconstruct the trajectories of the radiation in space.

In both cases, the fast expansion movement of the piston could be triggered by external devices. This allowed them to record interesting events in cosmic rays or to work with the accelerators [3]. These detectors, which also serve as targets, were usually placed in strong (around or more than 2 T) magnetic fields in order to determine the charge and the momentum of the particles via the curvature of their trajectories [6]. These "photographic" or "non electronic" detectors were operated on relatively long cycles, of the order of a minute or a hundred milliseconds respectively for cloud or bubble chambers [7]. Indeed, after the recording step, remaining ions in the sensitive volume have to be drained and a recompression phase has to take place to get back to the initial state of the device.

[1]Awarded the Nobel Prize for Physics together with Arthur H. Compton.

[2]D.A. Glaser had experience with cloud chambers and was awarded the Nobel Prize in 1960 for his invention.

[3]The bubble chambers had to be operated synchronously with the particle beam from an accelerator. Indeed, in the case of bubble chambers, the positive ions produced by the ionizing particles serve as nuclei for the formation of the bubbles; the lifetime of these ions (around 10^{-10} s) is too short to trigger the piston movement leading to the superheated state [7].

Drop Formation in Cloud Chambers

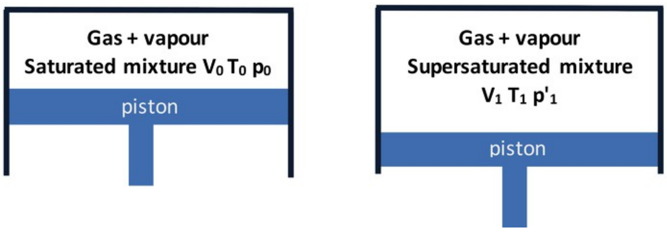

Figure 1: *Schematic illustration of an expansion cloud chamber.*

Assume a cylinder-piston arrangement (Figure 1) which contains a mixture of a gas such as air and a condensable vapour such as alcohol. Let V_0 be the volume of the cylinder and T_0 the temperature of the gas-vapour mixture before expansion. If the condensable vapour is in equilibrium with a free horizontal liquid surface at temperature T_0, then the pressure p_0 due to the vapour is the saturated vapour pressure. The mass m_0 of vapour in V_0 can be determined from the ideal gas law:

$$p_0 V_0 = \frac{m_0}{M} R T_0 \tag{1}$$

where M is the molecular weight of the vapour.

Immediately after a sudden expansion we get a larger volume V_1 and a lower pressure p_1' of the gas-vapour mixture with the same mass of vapour as before expansion because condensation does not yet take place:

$$p_1' V_1 = \frac{m_0}{M} R T_1 \tag{2}$$

The new temperature T_1 of the gaseous mixture is lower; it can be computed from the relation characterizing an adiabatic process:

$$\frac{T_1}{T_0} = \left(\frac{V_0}{V_1}\right)^{\gamma-1} \tag{3}$$

with γ the ratio of the specific heats for the gas-vapour mixture; γ values stand from 1.3 to 1.7 for commonly used gas or vapours in cloud chambers, see Tables of references [6, 10]. The lowering of the temperature corresponds, however, to a lower saturation pressure p_1 as shown on a typical vapour pressure vs. temperature curve (Figure 2) and the gas gets supersaturated before condensation takes place. If p_1 is less than p'_1, we get an unstable situation of supersaturation; it means that the pressure of the vapour p'_1 is too great to allow it to be in equilibrium with a plane liquid surface at temperature T_1. Some of the vapour will then condense on "condensation centres" until the pressure of the vapour p'_1 falls to p_1. The situation is then described by:

$$p_1 V_1 = \frac{m_1}{M} R T_1 \quad (4)$$

with a remaining mass of vapour m_1 ($m_1 < m_0$).

The ratio V_1/V_0 is called the expansion ratio. Its value leading to condensation conditions depends on the gas-vapour mixture; for air-alcohol mixtures at 20°C, an expansion ratio of around 1.3 was necessary [9].

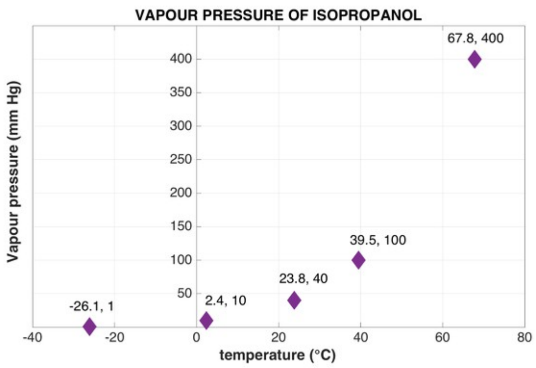

Figure 2: *Saturation vapour pressure versus temperature curve for 2-propanol. Drawn using data published in [28].*

Dust particles or ions of either sign can serve as centres for condensation because their presence reduces the saturation vapour pressure in their immediate vicinity. The mechanism of drop formation and growth is also related to the size and charge of the condensation centres. For a given supersaturation region, there exists a given critical drop radius below which the drop will evaporate and above which it will grow. It is also known that electrically charged drops promote nucleation, in this case condensation. More comprehensive information on this mechanism can be found in the references [6, 8, 9, 10].

It should be added that the lifetime of the condensation nuclei produced by the ionization is around 10 ms, the time needed for the droplets to grow to a size where they can be photographed is around 100 ms whereas the time for recycling the chamber to be ready for the next event is a few minutes [7]. The slow operation of the device explains why cloud chambers became obsolete end of the 1940s.

Some Contributions of Cloud Chambers to Particle Physics

At the beginning of the 20th century, numerous experiments were carried out to study terrestrial radioactivity and cosmic rays using expansion type Wilson cloud chambers. They led to major discoveries that paved the way for particle physics. The discovery of the antielectron by Carl D. Anderson[4] in 1932 should be mentioned in first [11]. A few years later, in 1936, Carl D. Anderson and his assistant Seth Neddermeyer discovered the muon lepton[5] in their search for the mesotron or Yukawa particle [12].

Another important contribution was made by Patrick M. S. Blackett[6], who designed and built with his team in Cambridge Laboratory, the first Wilson chamber controlled by external counters [13]. Together with Giuseppe P. S. Occhialini, he obtained in 1934 notable clichés of cosmic showers, proving conclusively the existence of the positron through the observation of electron-positron pairs created by high energy gammas, as predicted by Paul Dirac's theory.

Patrick M. S. Blackett also discovered a positively charged particle heavier than the mesotron, the existence of which was questioned until the strange kaon meson was confirmed in 1947 by Georges D. Rochester and Clifford C. Butler [14]. The latter published two famous photographs of cosmic ray events. One of these events is presented in Figure 3(a); it shows a neutral particle decaying

[4]The Nobel Prize in Physics 1936 was awarded to Carl D. Anderson together with Victor F. Hess.

[5]The lepton μ and meson π were definitely identified as different particles thanks to nuclear emulsion clichés recorded by Powell, Lattes and Occhialini in 1947.

[6]The Nobel Prize in Physics 1948 was awarded to Patrick M. S. Blackett "for his development of the Wilson cloud chamber method, and his discoveries therewith in the fields of nuclear physics and cosmic radiation" in 1948.

into two charged pions ($K_0 \rightarrow \pi^+\pi^-$) and is called a V-shaped event.

Louis Leprince-Ringuet performed studies on cosmic showers recorded at high altitudes; his book "Les mesotons" [15] includes remarkable clichés of cloud chambers. L. Leprince-Ringuet also coined the name "hyperon" for baryons other than nucleons.

The first strange baryon was observed in a cloud chamber as can been seen from the cliché on the Figure 3(b) ($\Lambda \rightarrow \pi + p$). One can notice the difference in ionisation density for both tracks: a denser droplet concentration explained by a higher energy loss density is observed for the proton which is heavier than the pion, as expected from the Bethe-Block energy loss expression [7].

We should not forget the famous cliché of the Joliot-Curie where we see a long track of a recoil proton emerging from the interaction of a neutral particle with a nucleus of the chamber material. The neutral particle was interpreted as a very high energy photon by the Joliot-Curie, whereas it was actually a neutron [16]. This cliché had been recorded just before the Chadwick's discovery of the neutron in 1932.

Two Types of Cloud Chambers

A variant of the *expansion* cloud chamber called *diffusion* cloud chamber was developed in 1939 by Alexander Langsdorf [17]. The diffusion device is illustrated schematically in Figure 4 and also consists of a transparent vessel filled with a gas-vapour mixture at the saturation pressure of the vapour, but there is no piston in the detector. Another method is used to obtain a supersaturated region.

As the name suggests, the diffusion cloud chamber operates by diffusing a condensable vapour from a warm unsaturated region to a cold region that becomes supersaturated. The vapour diffusion is downwards; the vapour comes from the upper warm end and goes to the lower cold end. Due to the cooling of the bottom of the chamber, a supersaturated region is formed, the extent of which depends on the geometric design and the temperature gradient. Table 1 compares the advantages and limitations of the two chamber types.

A number of combinations of gases and condensable vapours have been used in cloud chambers. In expansion-type chambers, air or argon with water and/or ethyl alcohol were commonly used. In a diffusion-type chamber air, hydrogen or helium for the gas with ethyl, methyl or isopropyl alcohol, at different pressures, were often used [6, 10].

Our homemade Cloud Chamber

The current homemade cloud chambers are based on the diffusion-type. The components of ours include a rectangular glass container, aquarium type, whose optimal dimensions are 23 x 35 x 17 cm^3 (Figure 5(a)), a metal aluminum plate whose dimensions are slightly greater than the cross area of the container, and an insulating polystyrene box whose dimensions are slightly greater than the plate ones (Figure 5(b)). In order to avoid light reverberations and to facilitate the visualization of the tracks, we covered one side of the metallic plate with black adhesive tape. Finally, we glued a 1 cm thick layer of felt to the bottom of the container using "fix-all" type glue and placed self-adhesive ribbon tape all along the periphery of the container, as can be seen in Figure 5(a).

As a source of cold, dry ice is used, either from industrial carbon dioxide gas cylinders or in the form of dry ice cubes. The gas inside the chamber is a mixture of air and isopropyl alcohol vapour. The liquid isopropanol we purchase is of high purity (99.5%).

Operating Procedure

The first step is to fill the insulating box with solid CO_2 and form a horizontal layer 2-3 cm thick. At the same time, we spray alcohol on the felt in order to soak it with liquid. The black metal plate is then placed on the dry ice layer and soon afterwards we turn the glass container upside down and place it carefully on the black metal plate. In a dark room, we illuminate from the side in low-angled light. The airtightness can be checked if there are no wisps of white mist entering the chamber from the edges of the container.

The liquid isopropyl alcohol begins to evaporate from the warm side of the chamber; the vapour cools as it falls down through the air and forms a

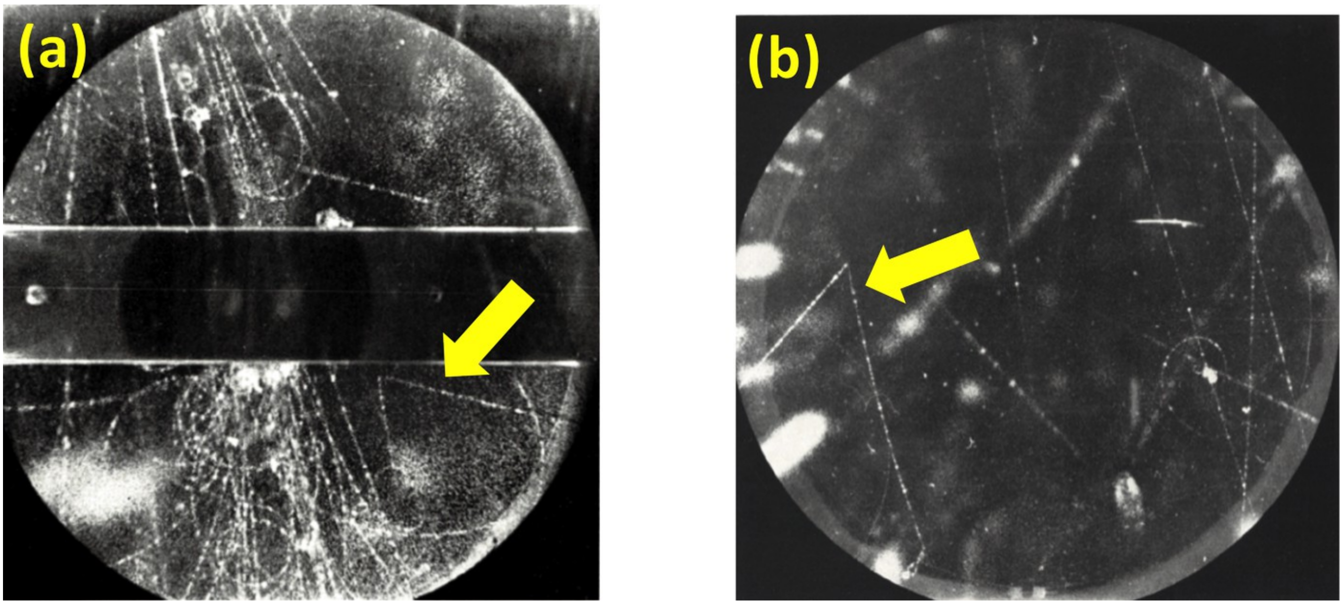

Figure 3: *Historical clichés of cloud chambers showing V shaped events of charged particle tracks. (a) A neutral meson K decaying into a pair of opposite charged pions. Image retrieved from http://www.cloudylabs.fr/wp/wp-content/uploads/2014/03/First.png. (b) A neutral baryon Λ_0 decaying into a proton and a negative pion. Image retrieved from http://www.cloudylabs.fr/wp/wp-content/uploads/2014/03/17.png.*

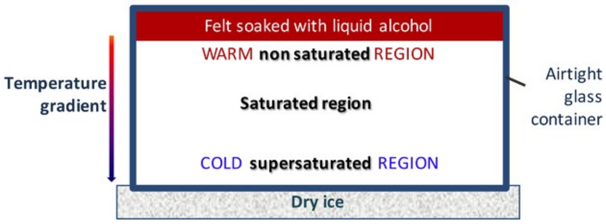

Figure 4: *Schematic illustration of a diffusion cloud chamber.*

layer of "fog", "rain-like mist" or "misty cloud-like" above the cold side of the chamber bottom. This "shallow pool of fog" of about 5 cm thickness formed above the bottom plate is the supersaturated sensitive region.

In most cases, we can observe the first ionizing particle trails after a few minutes. Some typical clichés are given in Figures 6. It should be noticed that the coiled trails are not static; they move downwards under the effect of convection currents and disappear quite quickly.

The chamber operates continuously for a period of time ranging from half an hour to an hour. The end of the visualization occurs when many long, thin trails are observed, making the images confusing, or when more and more alcohol vapour condenses on the lower metal plate, forming a liquid layer, which looks like a "mirror" preventing a clear visualization.

Trials & Errors, Advices

To build our first prototypes of cloud chambers, we were inspired by the reference [18]. These prototypes were made from commercial containers of different heights; the optimal functioning was achieved with containers of rather low height (less than the width). Today, we order our glass containers in the appropriate dimensions from an aquarium shop.

A strong light source is absolutely necessary to illuminate the droplet traces and should be directed towards the bottom plate of the chamber. If the light is too weak, the traces cannot be seen. A LED torch is recommended.

Plastic containers should be avoided as well as the black paint on the metal plate, as suggested for example in references [19]; the plastic will become opaque over time and the paint will disappear due to the liquid alcohol condensing on it.

In order to accelerate the evaporation of the alcohol from the felt, we heated the upper surface by placing hot water bottles on it (Figure 5.B) or by using an infrared lamp; this action proved unnecessary. We can therefore conclude that a temperature gradient of around 80°C (+20 to -60°C[7]) over 20 cm is sufficient. Furthermore, it

[7] Temperature measured at the bottom plate level; -70°C was measured in the dry ice insulating box.

Table 1: *Comparison of the characteristics of the two types of cloud chambers*

	Expansion-type	**Diffusion-type**
Mechanical design & operation		Simpler(*)
Time for observation	Repeated short intervals	Continuous and longer
Sensitive region	Larger: entire volume	Layer of a few cm thickness
Sensitive layer arrangement	Vertical or horizontal	Horizontal only
Trigger of the recording of interesting events	Possible	
Operation in high radiation background	Easier	Difficult (**)
Placement of absorbers inside the sensitive region	Possible (***)	

(*) there is no pressure resistant glass container, nor moving part.
(**) the ion density may become high enough to remove the supersaturated condition and thus prevents the appearance of the tracks.
(***) possibility to develop an electromagnetic calorimeter by placing parallel lead plates or possibility to determine the upward/downward direction of passage of the particle by measuring the track curvature if a magnetic field is applied (ionizing particles lose a part of their energy crossing a solid absorber).

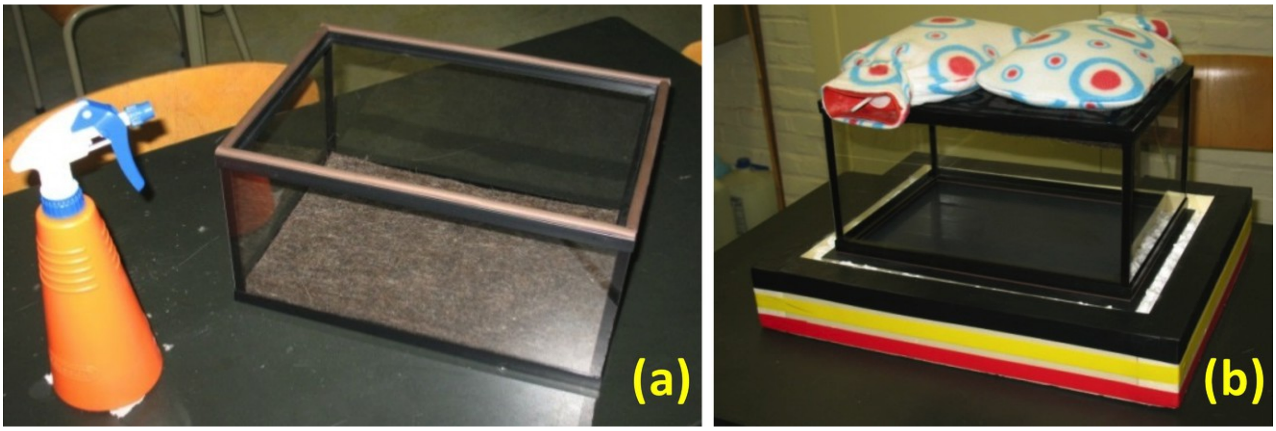

Figure 5: *Photos of our homemade cloud chambers. (a) Glass container with the felt glued on the bottom and an auto-adhesive sealing joint all along the periphery; the sprayer containing liquid alcohol is seen on the left. (b) The glass container turned over and put down on the black metallic plate which is placed on the dry ice. Hot water bottles are seen on the top of the container.*

seems that the radiation trails were more stable without additional heating because the convection currents were slower.

A crucial point to mention is the airtightness of the container. Our first prototype was sealed with a black electrical tape around the outer edge of the container; this did not allow any successful observation. Subsequently, we sealed our chamber with a commercial self-adhesive sealant in the form of a hollow tube that flattens when pressed (such as, for example, insulating door tape): see the brown structure on top of figure 5A.

A second crucial point is the high purity of the liquid isopropanol we use: $\geq$ 99.5%. Tests with alcohol of lower purity led to a difficult observation. The optimal amount of liquid alcohol to spray was determined to be about 40 mL for a felt surface of 23 x 35 cm^2.

Observations

A variety of informations can be obtained from the observation of the droplet trails in our cloud chambers. Counting the individual tracks can give a measure of the cosmic ray flux of which 75% is expected to be muons. We observe a rate of about one charged cosmic ray per second[8] passing

[8]Most cosmic muon tracks are vertical and therefore more difficult to observe than inclined tracks.

through our chamber (cross section = 23 x 35 cm^2). Figure 6(a) shows what most vapour trails look like; they could be described as "curls of mist" or "fog loops".

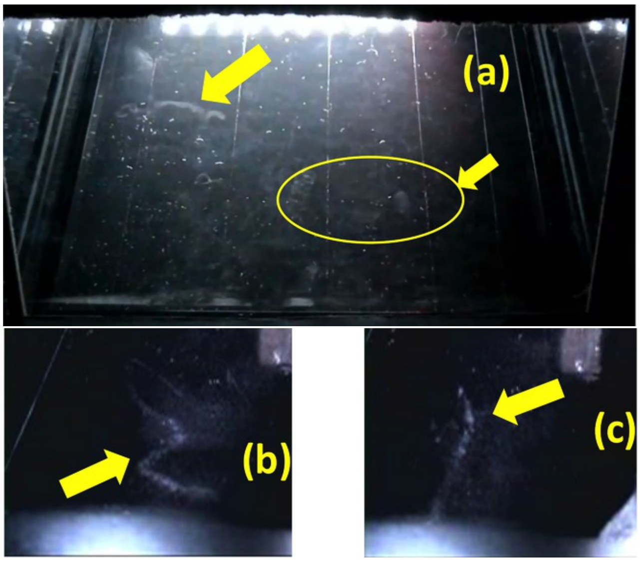

Figure 6: *Trails of vapour observed with cosmic rays. (a) Curls of mist (b) Zig-zag shape due multiple Coulomb scattering. (c) Kink due to an interaction with an atom of the sensitive medium or corresponding to a decay with a neutral particle emitted as well.*

Tracks of beta and alpha particles can also be detected using slightly radioactive objects such as a piece of uranium glass[9] or a granite mineral rock. A radiation sound monitor can give an idea of the level of radioactivity before placing the object on the metal plate and closing the chamber. The level of this "telluric radiation" can then be compared to the number of observed trails coming from the object. It should be pointed out that gamma rays also escape from the radioactive objects, so the count rate of the trails is lower than the count rate recorded by the monitor.

Cloud Chambers allow us to visualize not only the path of the ionizing particle, but also the density of droplets per cm of track length; the latter is related to the specific ionization and therefore to the nature of the particle. We can then proceed to study the structure of the observed trails. Each type of radiation has its own signature or ionization track pattern. Depending on the velocity, it is expected that:

- slow electrons lead to chaotic trajectories due to multiple scattering;
- fast electrons or muons show straight and rather long lines, showing a low density of ionization;
- alpha particles lead to straight, short and dense trajectories.

[9] Nickname is Vaseline glass.

Figure 6 shows typical trajectories observed in our cloud chambers operating with cosmic rays, while Figure 7 shows charged radiation trails emitted from a small granite rock. Figure 7(b) also includes a V-shaped event involving two tracks from the same point in space created by a neutral particle. This can be interpreted as a decay of a neutral cosmic particle into two charged particles ($K^0 \rightarrow \pi^+\pi^-$ or $\Lambda^0 \rightarrow \pi^- p$) or as a conversion of a gamma ray (γ + nucleus $\rightarrow e^+e^-$). Another possibility could be a nuclear interaction of a neutral cosmic ray on a nucleon.

Other Cloud Chambers

From the 1950s onwards, commercial diffusion cloud chambers have been proposed [20, 21]. In order to ensure long observation periods, i.e. to maintain the supersaturation condition, some models incorporate a continuous alcohol supply, a performant refrigeration system and apply an electric field of around 50 V/cm to remove spurious electric ions from the sensitive region. Some smaller models use Peltier cells for cooling.

Cloud chambers are or have been exploited in research centres such as CERN [22], in the ISOTOPOLIS information center in Dessel [23], or in other outreach activities [24]. "Atomic Energy Laboratories" kits, including cloud chambers, were even offered as toys to children in the 1950s. [25].

It can be added that a very sophisticated chamber has been developed by the CLOUD experiment at CERN. The CLOUD collaboration uses particle beams to study the influence of the passage of charged particles in the formation of clouds and thus investigates the influence of cosmic rays on our climate [26]. Finally, the "Cloudylabs" website providing a lot of information about cloud chambers and related physics should be mentioned [27].

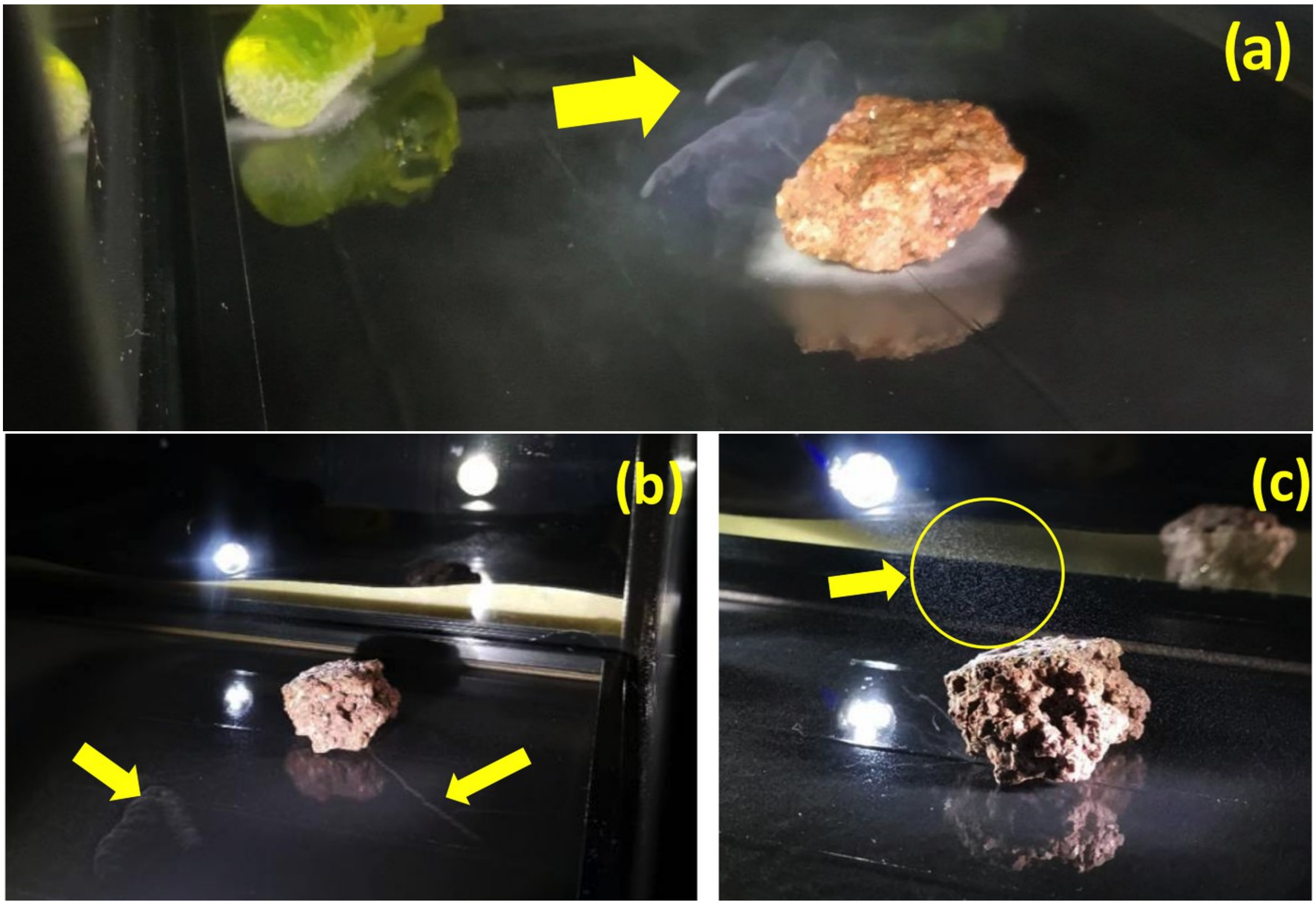

Figure 7: *Trails of vapour observed using a granite rock. (a) Short dense tracks, 2 to 3 cm long (alphas). (b) V-shaped event interpreted as the decay of a cosmic particle and a long trail coming from the rock interpreted as the one of an electron. (c) Mist constituting the sensitive medium of the chamber and some trails coming from the rock.*

Conclusion

One hundred and ten years after the invention by Charles Wilson of the expansion-type cloud chambers, a plethora of models of diffusion type cloud chambers are still in use. These chambers provide visible evidence of radioactivity by showing the traces of ionizing particles traversing a sensitive medium made of air supersaturated with a condensable vapour. The simplicity of construction and operation of diffusion cloud chambers has found important applications. In addition to public demonstrations, experiments with this device can be used to approach or extend knowledge in several areas of the physics lessons from thermodynamics to nuclear and particle physics.

At the UMONS Nuclear Physics Laboratory, we have constructed and successfully tested diffusion cloud chambers based on airtight glass containers where a saturated isopropyl alcohol vapour is cooled to supersaturation as it diffuses into a region kept cold by solid carbon dioxide.

Along with the cloud chambers, spark chambers are considered important historical detectors for observing radiation not visible to the naked eye. Our next project is to build and operate a spark chamber in collaboration with the MuMons, centre of diffusion of arts & sciences of the University of Mons.

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