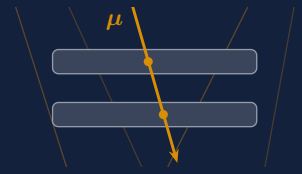


MicroCosmos [μ -Cosmos]

A cosmic-ray muon detector built from two Geiger tubes and an Arduino

Cédric Vanden Driessche, physics teacher, Lycée Charles de Gaulle, Caen, France
cedric.vanden-driessche@ac-normandie.fr



≈ US\$175

of off-the-shelf parts
(about 150 €)

no soldering

coincidence logic is
ten lines of Arduino code

1.2 muons/min

coincidence rate
measured at sea level

146 m⁻² s⁻¹

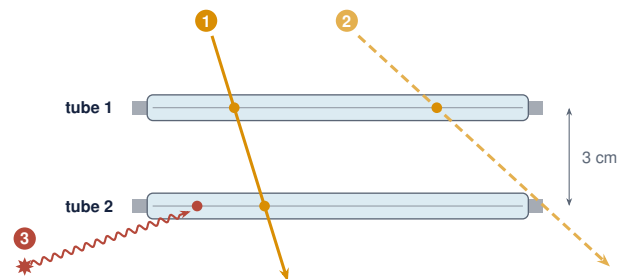
measured muon flux
(textbook value ≈ 170)

Why build it?

Cosmic-ray muons are free, harmless and present in every classroom, and they open a door to radioactivity, counting statistics and special relativity. Scintillator detectors such as the QuarkNet CRMD do this very well, but not every school can have one. MicroCosmos is a modest alternative: it repeats the 1929 coincidence experiment of Bothe and Kohlhörster with two ready-made Geiger modules, and replaces Rossi's vacuum-tube coincidence circuit by a few lines of code that students can read and change.

1 The principle: coincidence

A single Geiger tube clicks for any ionizing particle: β and γ rays from natural radioactivity as well as cosmic rays, about 0.5 count per second in total. A sea-level muon travels close to the speed of light and crosses matter almost undisturbed, so it fires two stacked tubes at the same instant. Two unrelated background counts almost never fall within the same millisecond. Counting only the coincidences N_{12} therefore selects the muons.



- 1 muon through both tubes: two simultaneous pulses, $N_{12} + 1$
- 2 inclined muon misses tube 2: not counted (geometric acceptance 19.5%)
- 3 β or γ from natural radioactivity: one tube only, rejected

Fig. 1 Two stacked Geiger tubes used in coincidence. Each DFRobot module holds an M4011 tube (10 mm × 88 mm, about 7 cm² of sensitive area).

2 Shopping list

Qty	Part (prices are indicative)	US\$
2	DFRobot Gravity Geiger counter module (SEN0463): high voltage and pulse shaping on board	2 × 70
1	Arduino Uno (or compatible)	25
1	DFRobot Gravity I/O expansion shield: plug-in 3-wire connectors	10
1	USB cable; laptop, or USB power bank and micro-SD logger for field work	
Total		≈ 175

3 Assembly in three steps

1. Stack the two modules, tubes parallel and 3 cm apart (Fig. 2).
2. Plug their 3-wire cables into digital pins 2 and 3, the two interrupt pins of the Uno. Each module idles at 5 V and drops to 0 V for about 0.3 ms when its tube fires (Fig. 3).
3. Upload `DetectionCosmiques.ino` and open the Serial Monitor (9600 baud): every second it prints the counts of each tube, the coincidences N_{12} and the elapsed time.

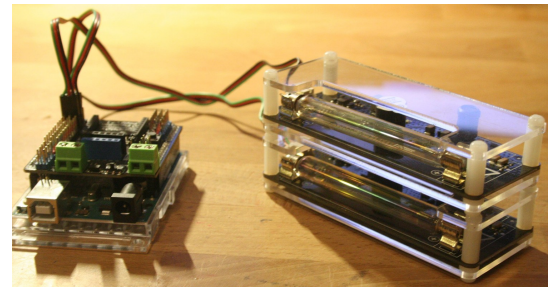


Fig. 2 The finished detector. The two Geiger modules are stacked on their own spacers; the Arduino carries the expansion shield.

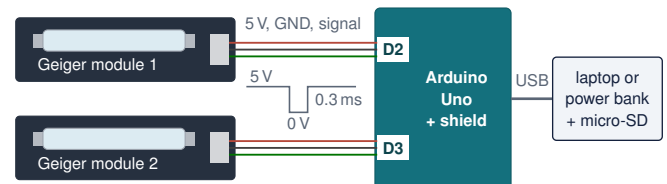


Fig. 3 Wiring. No extra electronics: each module's signal wire goes straight to an interrupt pin, and a falling edge marks the passage of a particle.

4 Coincidence in software

Each tube has its own interrupt routine that raises a flag. The main loop looks at both flags once per millisecond, counts a coincidence if both are up, then lowers them. This amounts to a 1 ms coincidence window, the resolution of Rossi's first circuit. With 0.5 background count per second in each tube, two unrelated counts share a window only about once per hour, against roughly 70 true coincidences.

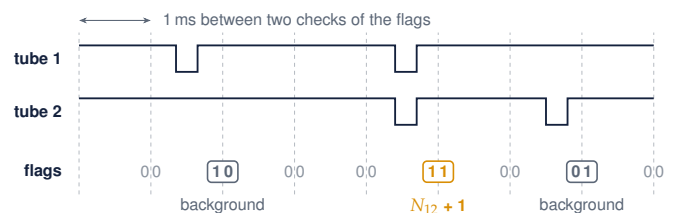


Fig. 4 Software coincidence. The loop reads the two flags every millisecond and counts a muon only when both tubes have fired in the same slice.

```
volatile int Etat1, Etat2; // one flag per tube
void GeigerISR1() { Impulsion1++; Etat1 = 1; } // tube 1
void GeigerISR2() { Impulsion2++; Etat2 = 1; } // tube 2
// in setup(): pins 2 and 3, falling edge
attachInterrupt(digitalPinToInterrupt(2), GeigerISR1, FALLING);
attachInterrupt(digitalPinToInterrupt(3), GeigerISR2, FALLING);
void loop() {
  for (int t = 0; t < 1000; t++) { // report every second
    delay(1); // 1 ms coincidence window
    if (Etat1 == 1 && Etat2 == 1) N12++; // a muon
    Etat1 = 0; Etat2 = 0; // lower both flags
  }
  // ... print Impulsion1, Impulsion2, N12, elapsed time
}
```

Core of `DetectionCosmiques.ino`, condensed. Students can change the window or add a third tube on a board with more interrupt pins.

5 Where the muons come from

Primary cosmic rays, mostly protons, strike the upper atmosphere and produce showers of short-lived particles. What reaches the ground is essentially muons. A muon is a heavy cousin of the electron (about 200 times its mass) that decays after $\tau = 2.2 \mu\text{s}$ on average. Even at the speed of light this is only $c\tau \approx 0.66 \text{ km}$ of flight, far less than the 10 to 15 km of air above us. That muons are counted at sea level at all is the puzzle the two experiments below let students resolve.

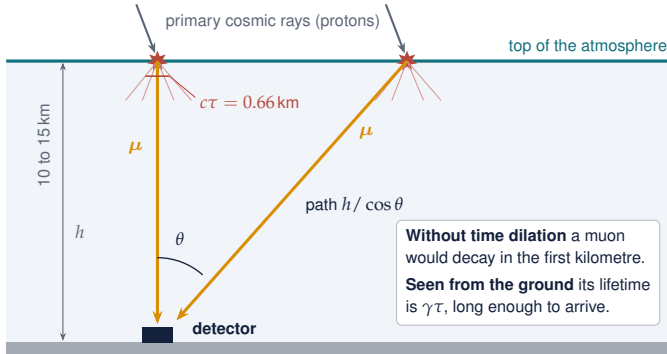


Fig. 5 Birth and flight of a muon (not to scale). A muon arriving at zenith angle θ has crossed a longer path, $h / \cos \theta$, than a vertical one.

6 Does it really count muons?

A run of 4 h 18 min (15 482 s) gave a steady rate of 0.0199 coincidence per second. Dividing by the sensitive area ($A = 7 \text{ cm}^2$) and by the geometric acceptance of the stack ($\epsilon = 19.5\%$ for tubes 3 cm apart, from a short Monte-Carlo script supplied with the code) gives the flux

$$\Phi = \frac{0.0199 \text{ s}^{-1}}{0.195 \times 7 \times 10^{-4} \text{ m}^2} \approx 146 \text{ muons m}^{-2} \text{ s}^{-1},$$

in line with the sea-level value of about 170 and with the 135 measured in the same school with a scintillator detector.

7 Experiment A: the zenith-angle distribution

A LEGO cradle tilts the stack by an angle θ from the vertical. Inclined muons cross more air (Fig. 5), so more of them are absorbed or decay on the way. Nine one-hour runs are well described by $N_{12} = 62.7 \cos^2 \theta + 8.2$.

Students can go further with a model for an “average” muon created at altitude h , combining absorption in air, proportional to the path, and decay in flight:

$$N(\theta) = N(0) \cos \theta \exp \left[-\frac{h}{v\tau} \left(\frac{1}{\cos \theta} - 1 \right) \right] + \text{noise}.$$

With the lifetime at rest, τ , the curve collapses far too fast. Replacing τ by $\gamma\tau$ and letting the fit choose the speed gives $v = 0.9986 c$, $\gamma = 19$; a later run with the tubes closer together gave $\gamma = 8.4$. Frisch and Smith measured $\gamma \approx 9$.

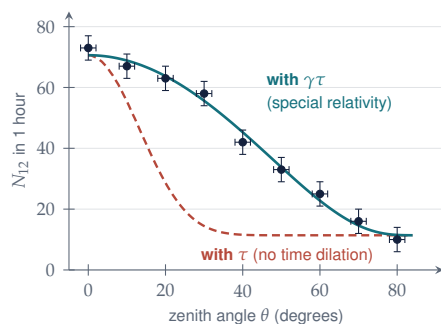
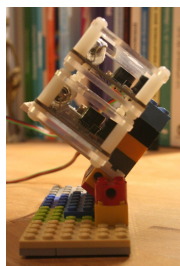


Fig. 6 Coincidences per hour against zenith angle ($\mu(N_{12}) = 4$, $\mu(\theta) = 2^\circ$) and the model with and without time dilation, for $h = 12 \text{ km}$. Right: the tilting LEGO support.

8 Experiment B: time dilation between sea and summit

In the spirit of Rossi and Hall (1941) and Frisch and Smith (1963), a group of students ran the detector on a USB battery at Caen (41 m) and at Alpe d'Huez (1850 m). Muons decay in flight, so their number should follow $N = N_0 e^{-t/\tau}$. Over the 1809 m between the two sites, at $v = 0.99 c$:

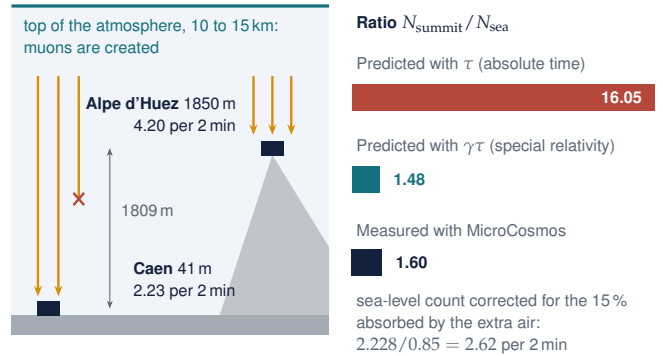


Fig. 7 Counting at two altitudes. Without time dilation there should be sixteen times more muons at the summit; the detector finds 1.6 times more.

$$\frac{N_{\text{summit}}}{N_{\text{sea}}} = e^{\Delta z/(v\tau)} = 16.05 \quad \text{but} \quad e^{\Delta z/(\gamma v\tau)} = 1.48.$$

The measured ratio, $4.20/2.62 = 1.60$, sides clearly with Einstein.

9 In the classroom

- **Mind the count rate.** With 7 cm^2 of tube, one point of the angular curve takes an hour, against five minutes with a scintillator detector. The low price is the answer: a class set of ten detectors pooling ten-minute runs, one angle per group for an hour, or volunteers starting one run a day.
- **One tube is already a lab.** A second sketch, MicroCosmosRadioactivite.ino, counts the pulses of a single module every 10 s: histograms and type-A uncertainty, inverse-square law, shielding, with a thorium lantern mantle or a potassium salt from the chemistry store.
- **Take it outside.** On a power bank with a micro-SD card the detector runs alone: mountain, aircraft, or a sealed jar at the bottom of a pool to test absorption by water.
- **Limits.** Geiger tubes cannot measure the muon lifetime directly, which requires muons stopping in a scintillator, and the module is not a dosimeter.

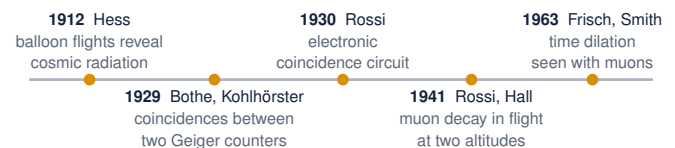


Fig. 8 The experiments that students re-enact with MicroCosmos.

Code (GPL v3): github.com/CedricVdd/MicroCosmos

The sketches print in French: *nombre impulsion* = counts of a tube, *nombre de coincidences* = N_{12} , *duree experience* = elapsed time (s).

Read more. C. Vanden Driessche, “MicroCosmos, un détecteur de particules à base d’Arduino”, *Bull. Un. Prof. Phys. Chim.* n° 1066 (Nov. 2024, in French). P. Singh and H. Hedgeland, *Phys. Educ.* **50**, 317 (2015). D. H. Frisch and J. H. Smith, *Am. J. Phys.* **31**, 342 (1963). B. Rossi, *Cosmic Rays*, McGraw-Hill (1964).

With thanks to the French programme *Sciences à l’École*, whose scintillator detector served as the reference.