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Rossi’s coincidence circuit: a reconstruction for educational purposes, with period instruments

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Abstract: The “Path of Science” in Arcetri is being set-up: it is a museum itinerary on the hill of Arcetri, near Florence, promoted by the University of Florence, the National Institute of Nuclear Physics (INFN), the National Institute of Optics (INO) and the Arcetri Astrophysical Observatory (OAA-INAF). As part of this project, which includes also the *villa*, where Galileo spent the last years of his life, a small museum will be set-up in the old headquarters of the Physics Department, where the KN3000 accelerator, switched off in 2003 and still located there, will be open to the public. This stage of the path will focus on the history of elementary particle and nuclear physics research in Florence, from about 1930 to the beginning of the new millennium. In recent months, we fortunately recovered at the “Fondazione Scienza e Tecnica” in Florence some large Geiger-Müller (G-M) tubes and a number of different vacuum tubes that had belonged to the University’s Institute of Physics. In this context, we considered to reconstruct the Rossi’s coincidence circuit, which had been conceived just within the walls of the Arcetri Institute. Apart from the power supply for vacuum and Geiger tubes based on modern technology, the design approach was as philological as possible. The apparatus will be part of the detectors of background radiation and cosmic rays, running in the museum and showing to visitors the relevant spectra and counting rates. In this communication we describe the phases of design, assembly and test of the circuit, which is actually fully efficient and allows to detect cosmic rays and to disentangle their “hard” and “soft” components, also providing realistic estimates of their flux at the ground level.

Keywords: Cosmic rays, Bruno Rossi, Arcetri, Coincidence circuit

1. Introduction

The construction of the new Physics Institute in Florence was promoted by the physicist Antonio Garbasso (Casalbuoni, Dominici & Mazzoni, 2021) on the hill of Arcetri; the building was inaugurated on November 7, 1921. In the following years, the Arcetri Institute rapidly became an important research center, where many young physicists were active. At that time and in the following years they provided fundamental contributions to Physics (Enrico Fermi, to cite the most famous one). The experimental research of the first period mainly focused on both nuclear physics, especially radioactive decays, and cosmic rays (Della Corte, sd). Among the physicists recruited by Garbasso, since 1928 the young Bruno Rossi, then twenty-three years old, initiated in Arcetri its pioneering research on cosmic rays. The human and scientific experience of Bruno Rossi has already been described in various articles, books, and memories written by Rossi himself (for example, see Rossi, 1964; Rossi, 1981; Rossi, 1987; Leone, Mastroianni & Robotti, 2005; Bonolis, 2011; Peruzzi, 2015).

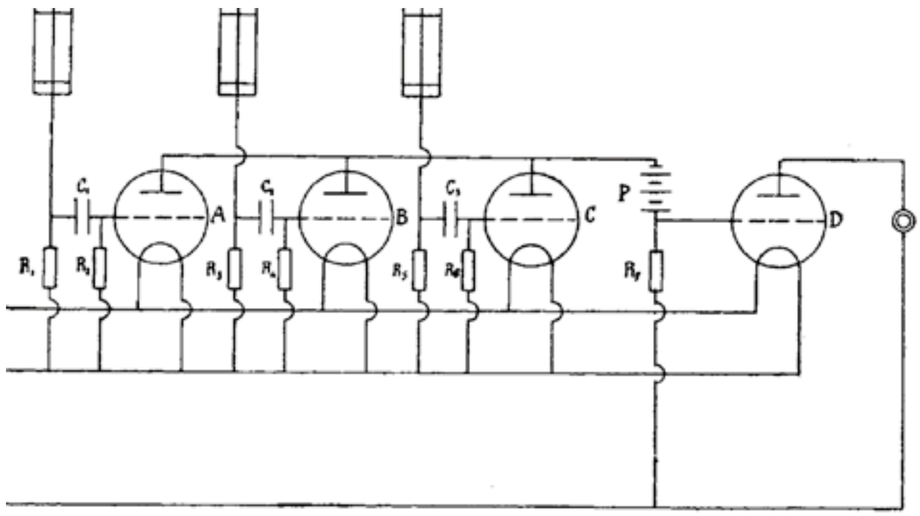

Fig. 1. Original schematic of the Rossi's coincidence circuit, from (Rossi, 1930). We can find some resistors (R_1—R_7), capacitors (C_1—C_3), triodes (*A*, *B*, *C*, *D*), three Geiger-Müller tubes, on the top, and a headphone on the right branch to detect the variation in the anode current of the *D* valve. There are also some batteries to provide the necessary power supply. Please note that batteries in this image follow the polarity convention valid at that time and opposite to that used today: here the long dash corresponds to the negative terminal, as was the custom in Italy in those years.

One can find the description of Rossi's coincidence circuit, shown in Fig. 1, in the seminal paper appeared on *Nature* (Rossi, 1930). This circuit allows to detect the coincidence of the electrical signals coming from several G-M detectors (three in the figure): by selecting the events in which an ionizing particle passed through all the tubes mutually oriented in specific geometric configurations, it is possible to count the cosmic particles and understand the mechanisms of their interaction with matter. The circuit is based on vacuum valves (triodes A, B, C, D); the grids of A, B and C are connected to the anodes of three G-M tubes, sketched on the top of the picture. The passage of an ionizing particle in a G-M tube makes the grid potential of the corresponding triode negative. *The grid of the valve D (for the introduction of the auxiliary battery P) is at a slight negative potential. This potential varies very little when only one or two counter tubes are working, while it undergoes a sudden rise when, for the simultaneous working of the three counter tubes, the current is interrupted in all the three valves* (Rossi, 1930). When the grid of the fourth triode becomes positive, the variation of the anode current is detected by a headphone or a loudspeaker in the right branch of the circuit.

This arrangement represented a real novelty in signal treatment, constituting the first implementation of a logic AND of individual signals. The Rossi's coincidence circuit is today considered as a precursor of the AND logic gates used in digital electronics and computers.

2. Our reconstruction of the circuit

Our reconstruction started when some G-M tubes well apt for cosmic rays detection (70 cm long and 3 cm in diameter) and a number of different vacuum tubes were found in the shelves of the "Fondazione Scienza e Tecnica" Museum in Florence; all of them originally belonged to the University's Institute of

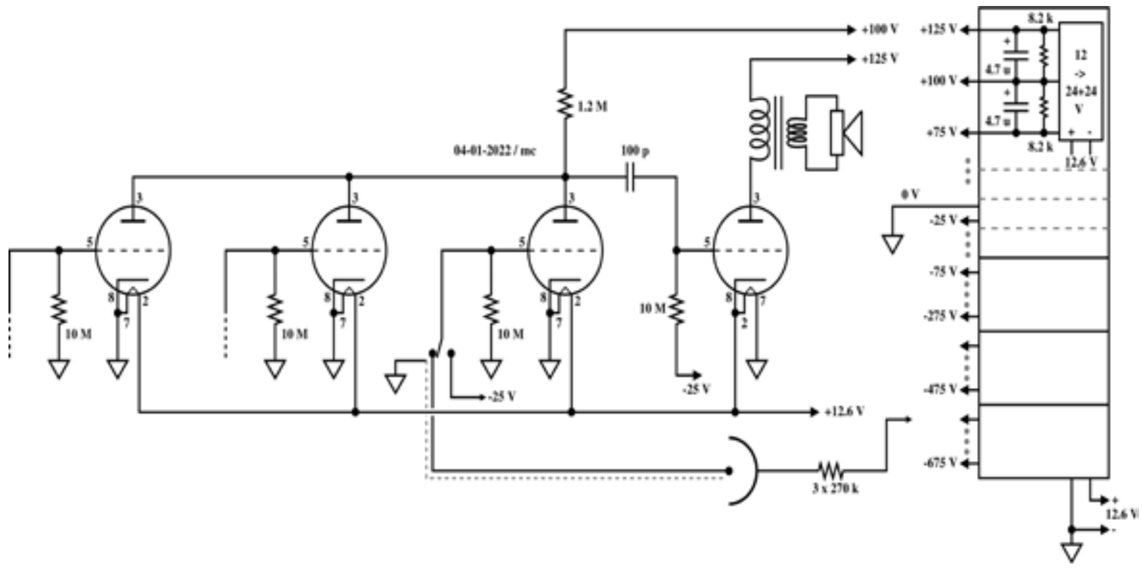

Fig. 2. Our reconstruction of the circuit. The switch in each channel allows to disable it, bringing the corresponding triode grid to -25 V. The HV module on the right powers the circuit and also the G-M tubes (one of them is sketched on the bottom).

Physics, where Bruno Rossi was active around 1930. Actually, the recovered instrumentation is not the original of Rossi, but is the one used in the next decade by the physicists who continued in Arcetri the experimental studies on cosmic rays. As a matter of fact, the G-M counters are of the self-extinguishable type, not yet available in the '30s. A prototype of a new "Rossi-like" circuit, based on these components, was rapidly drawn, assembled and tested (Fig. 2). By interfacing the circuit with a computer, counts from a single channel and two- or three-fold coincidences could be acquired, as channels 1, 2 and 3 can be switched ON/OFF independently of each other. The interface is based on the digital sampling of the signals by a sound card. In this way, coincidence events collected in time-intervals chosen by the user are counted, displayed in real time and recorded on the hard disk for off-line analysis. On the basis of this simple — though efficient — acquisition system, a series of measurements with cosmic rays was started, attempting to reproduce some of those obtained by Rossi in Arcetri.

Bruno Rossi describes in his books and papers the first measurements on cosmic rays performed with his apparatus:

A. Measures of G-M tubes efficiency;
B. Direction of incoming cosmic rays;
C. Magnetic deviation of cosmic rays;
D. Absorption of cosmic rays in matter;
E. Secondary radiation produced in matter by cosmic rays.

A. The coincidence of three aligned (i.e. parallel and lying on the same plane) detectors allows to measure the efficiency of a tube and its dependence on the applied voltage, by using as a trigger the coincidence of the other two. A threefold coincidence is less subject to random coincidences with respect to the twofold configuration, and this is particularly important for low-acceptance set-ups, for example for non-adjacent tubes.
B. Rossi determined the direction of arrival (that was found preferentially vertical) by comparing various configurations of aligned detectors (above each other, next to each other, etc.)

C. The magnetic deviation was studied by measuring the deflection of the penetrating particles through a bar of magnetized iron acting as a magnetic lens. Rossi found a small effect, non statistically significant; this basically negative result was *largely due to the presence of both positive and negative particles in the cosmic radiation* (Rossi, 1981), as understood in the following years.
D. The study of the absorption of cosmic rays was considered fundamental to discriminate their nature (γ-rays or charged particles). Rossi compared the number of coincidences in various configurations. With a lead plate placed over the detectors, the coincidences increased by some percent, compared to the measurements made with the same metal layer placed between the tubes. This was an indication that cosmic rays were composed of charged particles. Actually, the detailed comprehension of the observed phenomena came later, when the theoretical description of the interaction of high-energy γ-rays and electrons with matter was available.
E. The emission of secondary radiation was studied with a configuration of three G-M counters arranged in such a way that a single particle from cosmic rays could not produce a triple coincidence punching-through them: namely, the three cylindric detectors were parallel, not lying on the same plane but with their axes passing through the vertices of a triangle. Apart from random coincidences, whose rate is very low, a three-fold coincidence can be produced only when a secondary particle is generated in a material above the detector crossed by the primary particle. According to Rossi, in this set-up *the high rate of coincidences was astounding* (Rossi, 1981). The study of the dependence of the three-fold coincidences in such a configuration as a function of the amount of material above the counters permits to determine the so-called "Rossi curve".

3. Measurements with the apparatus

The determination of the "Rossi curve", performed for the first time in Arcetri, is of great educational interest, due to its importance in the history of elementary particle physics. Proposals have been made to use Rossi-like measurements on secondary production for educational purposes (Jackson & Welker, 2001). We therefore decided to focus our first tests with the reconstructed apparatus mainly to this issue. A photo of the box, housing the reconstructed circuit, along with the G-M tubes is shown in Fig. 3.

The counting rate of a single G-M tube due to natural radioactivity of the surrounding material and cosmic rays is roughly 12 Hz, while the three parallel and superimposed counters shown in the photo yield a coincidence rate of about 1 Hz (this value is in agreement with theoretical estimations based on the now-known cosmic ray flux and with the geometrical factor of roughly 120 cm^2 sr for this set-up). The random coincidence rate (r_{RC}) can be measured with the three G-M tubes far away from each other and lying along skew directions, in order to exclude a true single-particle trigger and to keep at minimum the number of coincidences due to Compton scattering among detectors. This random rate depends on the resolving time of the system, τ (assumed to be the same for any electronic channel) and on the individual rate in each branch (r_1, r_2, r_3):

$$r_{RC} = 3\tau^2 r_1 r_2 r_3$$

This formula (Knoll, 2000) has been used to estimate the resolving time τ, which came out to be of the order of 10^{-3} s for our system. It is to be noted that the measured resolving time depends on the decay time of the G-M signals at the input of the relevant triodes, mainly determined by the stray capacitance of the cable connecting the G-M anode multiplied by the resistance connecting the grid to ground (see Fig. 2).

We preliminarily measured the stability of the counts in a given time interval as a function of time, observing that all three detectors show a significant anti-correlation of the efficiency with the room temperature; a typical trend is shown in Fig. 4. The drift due to temperature change is definitely larger than statistical variations. Therefore, in order to perform significant measurements, it is necessary to keep the temperature variations during the data acquisition as small as possible or to record the temperature and to select accordingly the collected data.

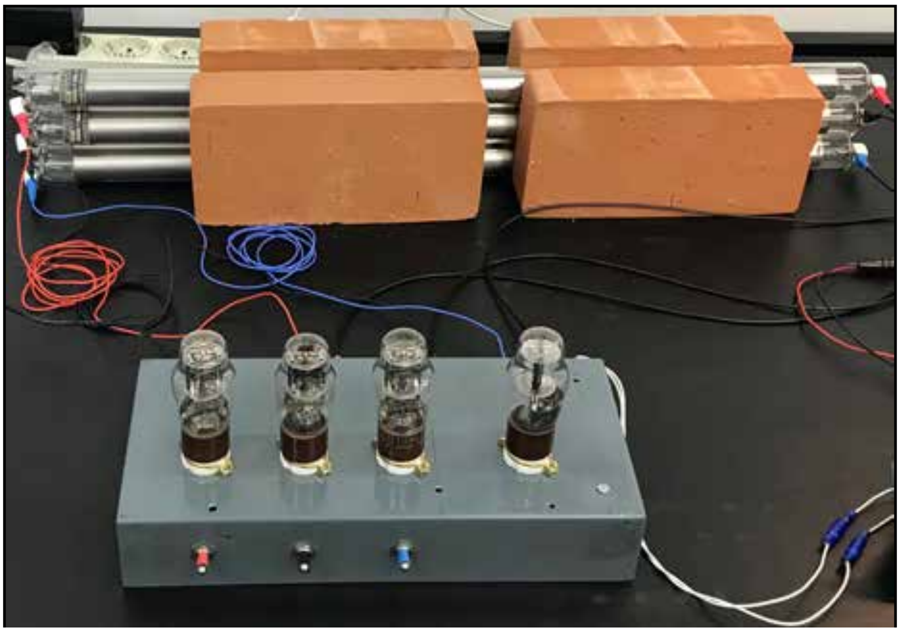

Fig. 3. A picture showing the reconstructed coincidence circuit (housed in the box) and the three G-M tubes on background, in this case aligned for the acquisition of cosmic rays coming from the vertical direction.

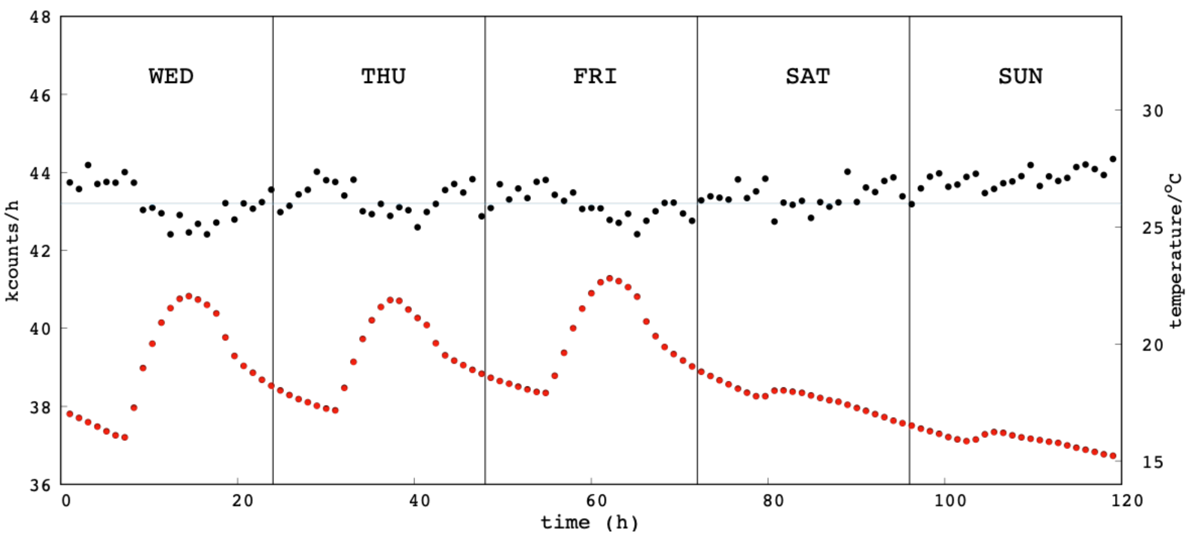

Fig. 4. *Black dots*: counts per hour registered by one of the G-M tubes for five subsequent days, independently of whatsoever coincidence. The scale, in kcounts/h, is on the left axis. *Red dots*: temperature of the laboratory, acquired during the measurements with a dedicated probe. The corresponding scale in Celsius is shown on the right axis. It can be observed that counts are anti-correlated with temperature (lower temperature corresponds to higher counting rate). Other G-M tubes show a similar behaviour.

In order to reproduce the "Rossi curve" we obviously adopted the geometry of the Rossi's set-up, placing the detectors at vertices of a triangle (Fig. 5). Above the detectors, we placed lead plates and we measured the coincidence rate as a function of their thickness. This is very similar to the Rossi's set-up, except for the additional few-cm thick lead absorbers that Rossi placed on sides and below the G-M tubes to reduce the background of environmental radioactivity.

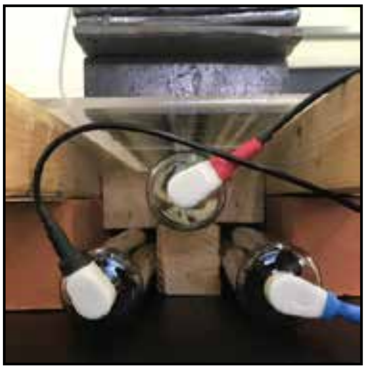

Fig. 5. Triangle-shaped arrangement of the G-M tubes.

In Fig. 6 we report the original "Rossi curve", i.e. the coincidence rate as a function of the lead thickness above the detectors, obtained by Rossi (three data sets show the results obtained with lead and iron, at different distances from the above shield).

> One sees that the lead curves (I and II) reach a maximum between 10 and 20 g/cm^2 of lead, which shows that the secondary partic*l*es have a range in lead of this magnitude. One then finds that, beyond the maximum, the curves drop much more rapidly than the absorption curve of cosmic rays at sea level; I interpreted this result as showing that the coincidences were at least in part produced by comparatively soft, secondary rays generated by cosmic rays in the atmosphere (Rossi, 1981).

As it was fully understood in the following years, this corresponds to the fact that muons are the penetrating ("hard") component of cosmic rays, while electrons associated to electromagnetic showers (produced in the atmosphere by the decay of neutral pions and muon themselves) are the highly interacting ("soft") component. The electrons-to-muons ratio in the cosmic radiation at sea level is about 0.002 for $E > 1$ GeV, but this value rapidly increases for lower energies (Workman *et al*. 2022).

In Fig. 7 we have the same measurement made with our apparatus. The trend is similar to that of Fig. 6, but the maximum lies at about 1 cm Pb (≈ 10 g/cm^2). We interpreted this result by the presence of additional material above the counters (for instance, the ceiling of the laboratory). Our intention is to repeat the measurements in an open-air set-up. Probably it was a very common set-up at the Rossi's time, as we know from some testimonies of the period:

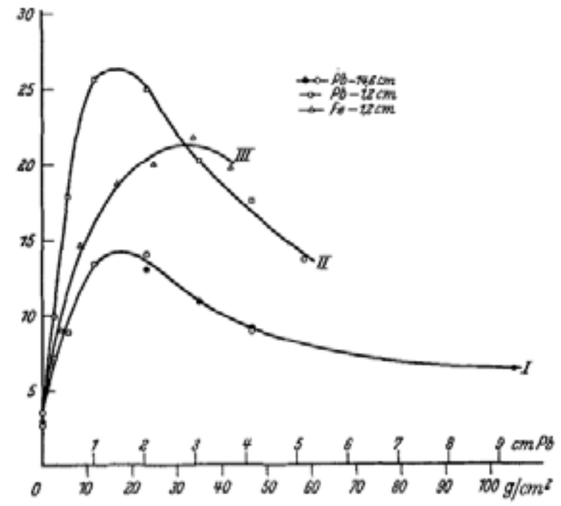

Fig. 6. Original picture (Rossi, 1933) showing the number of triple coincidences per hour in the triangle-shaped configuration, as a function of the lead thickness placed above the detectors. Three sets of measures correspond to different distances between the counters and the metal layers placed above them and also different absorbers (lead or iron). For curves I and II (lead) the maximum is around 1.5 cm Pb.

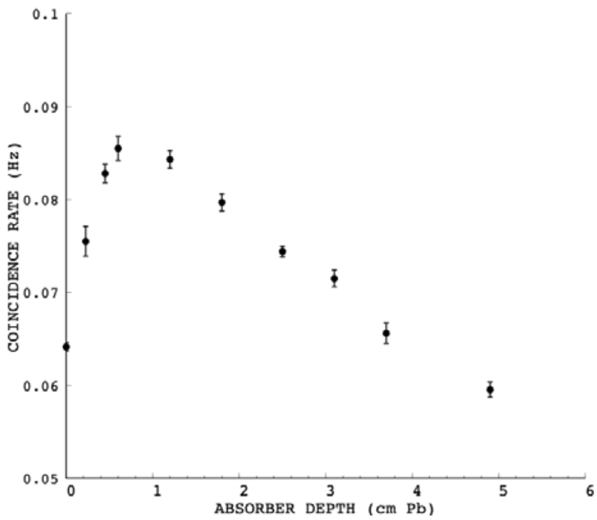

Fig. 7. Coincidence rate measured in our laboratory with the triangle-shaped arrangement of Fig. 5, as a function of the lead thickness placed above the tubes. The maximum of this curve lies at about 1 cm Pb. The absolute coincidence rate here cannot be directly compared with that of Rossi, because of a different geometry and characteristics of G-M tubes and shields.

> We came to the attic and to a large terrace where it was built a wooden hut in which a Franciscan friar supervised some Geiger counters and a registration. Professor Bernardini who accompanied us explained that P. Serafini was recording the cosmic ray showers produced in a lead layer (Della Corte, sd).

Moreover, we plan to deepen the interesting issue of the resolving time of the present circuit, by varying the resistor from grid to ground.

4. Conclusions

In view of the conclusion of the work of the new Arcetri museum, this experiment is of great interest. It will be shown to visitors, together with other detectors for measuring background radiation, in the place where Bruno Rossi had conceived and implemented these measurements. The philological reconstruction of this apparatus is also useful for physics students, who can thus better understand the first steps in the study of cosmic rays and particle physics.

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