Atti del XLIV Congresso Nazionale Sisfa - Firenze 2024 (2025), **43**_35, pp. 297–302
Doi:10.6093/978-88-6887-352-3-35

Revisiting Bruno Rossi's experiment on cosmic rays' secondary emissions: comparison with the original results

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Abstract: In this paper a reconstruction of a pioneering experiment on cosmic rays, originally devised by Bruno Rossi in Arcetri around 1930, is described. Geiger-Müller counters, arranged in a special triangle configuration, were used to study the secondary particles produced by cosmic rays when interacting with absorbing materials placed above the detectors. Modern techniques for data acquisition and analysis allow for fast signal timing. The obtained resolving time (about 1000 times shorter than Rossi's) allowed us to greatly reduce the number of random coincidences, mainly produced by environmental radioactivity, whose effect was prevented in the original Rossi experiment by surrounding the detectors with thick lead shielding on the side and bottom. The Rossi curve resulting from our measurement is very similar to the original one.

Keywords: Bruno Rossi, Cosmic Rays, Geiger-Müller Counters

1. Bruno Rossi in Arcetri

The Physics Institute of Florence, inaugurated in 1921 on the hill of Arcetri, rapidly became a prominent research center, where many young physicists made fundamental contributions to physics, especially in the period 1925-1932 (Casalbuoni, 2021). Enrico Fermi was the most famous component of this team. The experimental research of the first period mainly focused on nuclear physics, especially radioactive decays, and cosmic rays (Della Corte, sd). Among the physicists recruited by the Director of the Institute Antonio Garbasso, the 23-year-old Bruno Rossi, assistant professor since 1928, initiated in Arcetri its pioneering research on cosmic rays.

Crucial innovations in the field of cosmic ray physics are due to Bruno Rossi. One of his most significant contributions was the improvement of the coincidence method, already introduced by Bothe, which allowed detecting with great precision and efficiency correlated events of particles passing through different detectors. This method, developed through the use of Geiger-Müller counters, allowed Rossi to obtain more accurate data and to study the properties of cosmic particles with unprecedented detail. During the next sections, we will often refer to the methods used by Rossi and compare them with the techniques available today, also to highlight the difficulties that Rossi was facing. In these years, Rossi also worked with Giuseppe Occhialini, another brilliant Italian physicist. Together, they explored the properties of cosmic rays and helped clarify the nature of these particles. The human and scientific experience of Bruno Rossi has already been described in several articles, books, and memories written by Rossi himself (for example, see Rossi, 1964; 1981; 1987; Leone, Mastroianni & Robotti, 2005; Bonolis, 2011; Peruzzi, 2015).

2. The Rossi curve

One of Bruno Rossi's most significant contributions to cosmic ray physics is the Rossi curve, which describes the relationship between the intensity of the secondary radiation produced by cosmic rays and the thickness of the material they cross. Rossi performed experiments using lead and other high-density materials. The discovery and study of this curve have provided crucial information on the nature of the particles found in cosmic rays and their interactions with matter, paving the way for further developments in particle physics and astrophysics (Clark, 2005; Rossi, 1932).

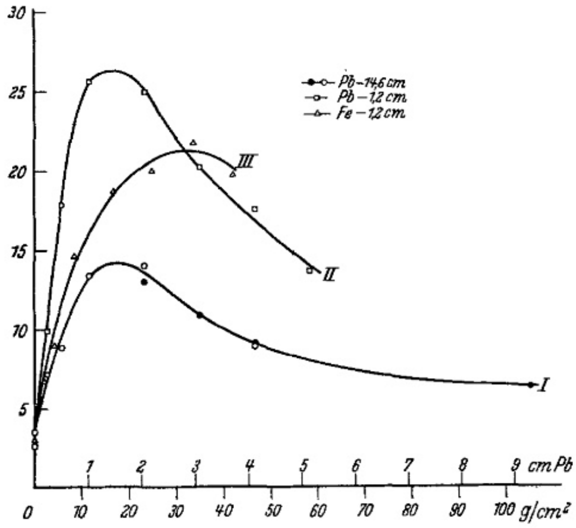

Fig. 1: The Rossi curve (from Rossi, 1933). The coincidence rate (events per hour) is reported as a function of the equivalent thickness of material placed above the counters. For curves I and II the absorber is lead, at different distances from GMTs; iron for III.

The Rossi curve has a peculiar characteristic: an initial increase of the intensity of secondary radiation when increasing the thickness of the crossed material, is followed by a maximum and finally by a decrease of the intensity. The curve, graphed by Rossi in one of his papers (Rossi, 1933) and reproduced in Fig. 1, was obtained by placing absorbers of different thickness (in this specific case, Pb and Fe plates) above three detectors (Geiger-Müller tubes, GMTs) arranged in a particular configuration, which we reproduce with three modern detectors (Fig. 2). Triple coincidence signals identified by Rossi's circuit in this 'triangle configuration' of GMTs cannot be activated by a single particle with a straight trajectory. At least two particles crossing the three detectors within the resolving time of the system are needed to trigger the system.

The behavior observed in the Rossi curve (Fig. 1) can be explained by three mechanisms:

1. Production of secondary particles: on the left side of the curve, when the crossed material is relatively thin, the intensity of the secondary radiation increases with increasing thickness. This is due to the fact that interacting cosmic rays (mainly the electromagnetic component thereof) produce secondary particles (once again photons and/or electrons) in the metal layer and have a sufficient energy for punching through it; these secondary particles are detected by Geiger-Müller tubes.
2. Absorption of secondary particles: as the thickness of the material increases, the intensity of the emerging secondary radiation begins to decrease, because the produced secondaries are absorbed by losing energy mainly through further interactions with the atoms of the material. Particles with lower energies are progressively stopped; only the most energetic particles are able to penetrate through greater thicknesses.

3. Maximum intensity: the presence of the two just described effects implies the existence of an optimal thickness, in which the intensity of detected secondary particles exhibits a maximum. This peak is an important indicator of the amount of energy transferred from the particles to the atoms of the crossed material.

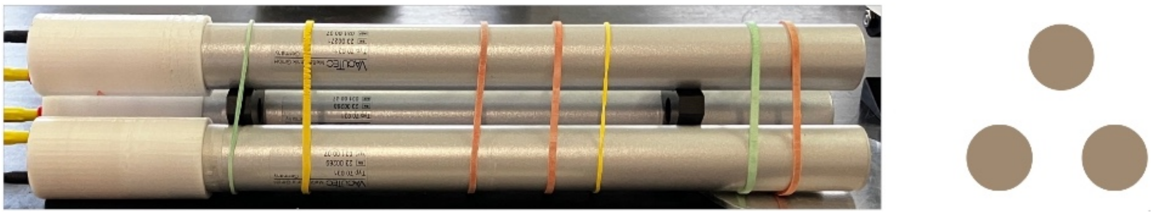

Fig. 2: The detector arrangement in our laboratory, which reproduces the original configuration used by Rossi. Our GMTs have a cathode diameter of 18 mm. On the right, a sketch of the arrangement in an orthogonal view.

Lead was one of the most used materials in Rossi's experiments to trace the absorption curve of cosmic rays. Lead, thanks to its high density and high atomic number, is particularly effective in both producing and attenuating secondary particles. Experiments with lead revealed fundamental details about cosmic ray interactions and helped clarify the nature of primary particles. Rossi realized that a hard component of cosmic radiation at sea level is made up of particles that interact very little with matter (today we know they are muons) while a soft electromagnetic component interacts frequently to form secondary radiation. With his triangle arrangement of GMTs Rossi implemented an optimal experimental condition to detect the secondaries. These results were fundamental to understand the penetration and absorption properties of subatomic particles, also providing an experimental confirmation of the theoretical studies by Bethe and Heitler. The coincidence of three detectors was obtained by Rossi with the circuit he invented and designed, based on triodes (Rossi, 1930). The time resolution of this circuit was roughly 1 ms; that means that, beyond true coincidences, two or more particles arriving by chance within this time interval, produce false (random) coincidences, which could not be distinguished from the true ones. Therefore, Rossi was forced to estimate the random coincidence rate, in order to subtract them from the total recorded number.

With a couple of detectors (for instance, GMTs) the frequency of expected random coincidences is given by the following expression:

$$\nu = 2\tau n_1 n_2 \tag{2.1}$$

where:

- n_1 and n_2 are the counting rates of the two Geiger-Müller tubes, usually referred to as "singles": they can be measured doing experiments with the individual tubes, placed in the same position as for the measurement;
- τ is the resolving time of the detectors, i.e. the minimum time interval to distinguish two events; it can be measured counting the random coincidences that occur in a dedicated set-up where the counters are sufficiently far away and misaligned from each other, so that true coincidences can be neglected. In this configuration, after measuring the rate of random coincidence events ν^* and the single counting rates n_1^* and n_2^*, we deduce the value of τ (a characteristic of the used electronics and detectors) from the formula;
- in this way, during the actual coincidence experiment, with the value of τ, n_1 and n_2 determined as explained before, from the formula it is possible to determine the expected random coincidence background ν (events per second) to subtract from the total number of coincidences once the experiment is concluded.

Moving on to the three detectors configuration, the formula becomes a little more complex. Assuming that the resolving time τ is approximately the same for all pairs of detectors, Rossi wrote (1933; Knoll, 2000):

$$\nu = 2\tau \cdot (n_{12}n_3 + n_{23}n_1 + n_{31}n_2) + 3\tau^2 n_1 n_2 n_3 \tag{2.2}$$

In this formula:

- n_{12}, n_{23} and n_{31} are the true coincidence rates of detector pairs, indicated by the digits in the subscript of n, so that the first three terms of the sum represent the random coincidence rates composed of true coincidences of two detectors and a single pulse from the third one;
- the last term gives the random coincidence rate due to independent signals of the three counters.

In order to apply this formula for estimating the random coincidences in the adopted "triangle configuration", Rossi, while still exploiting the previously determined value of τ and using the rate of the singles n_1, n_2 and n_3 in the current experiment, had also to determine the double coincidence rate for each pair of counters (n_{12}, n_{23}, n_{31}) with dedicated runs, while keeping the same geometrical configuration of the counters. The counting rates given in Fig. 1 have been obtained by subtracting the estimated random coincidence rate in every arrangement from the (total) measured coincidence rate.

3. Our reconstruction of the apparatus

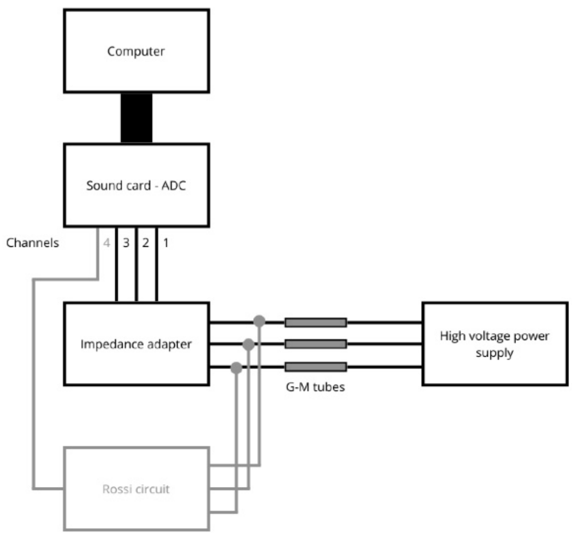

Fig. 3: Scheme of the apparatus.

In our reconstruction, we have the three detectors shown in Fig. 2, read by a 4-channel sound card, working as a sampling ADC. The fourth channel is used to digitize the output of the "Rossi-like" coincidence circuit, which we reconstructed in the past with a scheme similar to the original one (Carlà *et al.*, 2023). This fourth channel is useful for comparing the coincidence rate presumably observed by Rossi with our value, but it is not essential in order to reproduce the result of the experiment, as discussed in the following. A scheme of the acquisition system is shown in Fig. 3.

This novel acquisition system allows to sample data with 24 bit resolution at 192 kSample/s, thus obtaining a transcription of the GMT signals suitable for a precise timing: in this way the resolving time is expected to be significantly smaller than in the original apparatus. Data of the four channels, digitized by the sound card, are recorded on a text file for further analysis, provided a trigger condition set by the user is satisfied: trigger is activated when the involved signals cross a threshold level. In Fig. 4 we show the typical signals, obtained by plotting the sound card data of the four channels. These signals can be analyzed to obtain precise timing. In particular, the instant corresponding to the beginning of the signal is reconstructed by interpolating the experimental points with a third degree polynomial at a constant fraction of the maximum. The technique is known in literature (Bardelli *et al.*, 2004) and gives, in the present case, a resolving time of the order of 1 μs, even if the signals are sampled in steps of approximately 5 μs (corresponding to 192 kSample/s) [1]. Depending on the size and set-up of our

[1] Exploiting the fixed and large amplitude of the signals, a simpler and even more accurate timing has been obtained, as will be described in a forthcoming paper.

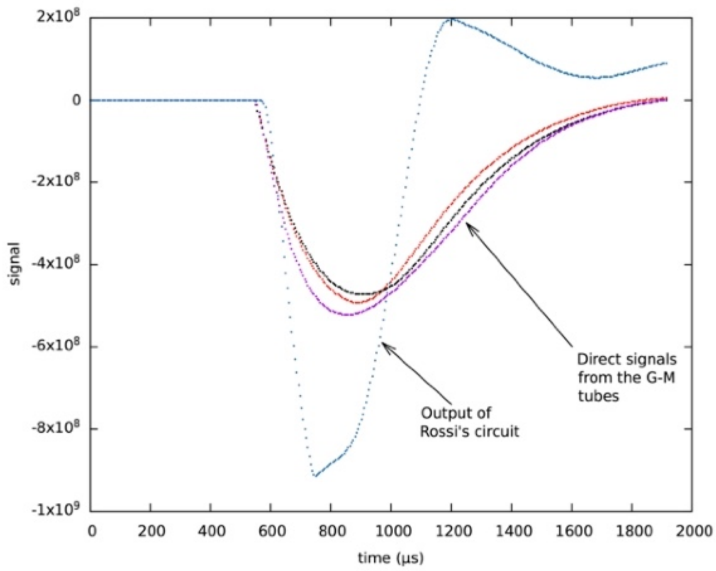

Fig. 4: Typical output of the sound card.

detectors, the system yielded a coincidence rate of a few tens of counts per hour: acquisitions of a few days were therefore necessary to collect the statistics needed to reproduce with the needed accuracy the Rossi curve. We made measurements with various thickness of lead (up to 50 mm) above the detectors, without any shielding around the GMTs.

In a previous version of the apparatus (Carlà *et al.* 2023) we used a single channel sound card to digitize only the output of the reconstructed Rossi circuit. As a consequence, we could count the coincidences of the signals, with a resolving time of approximately 1 ms, without investigating shape and timing of each signal. It is worth noting, as expected, that this value of the resolving time is well within the corresponding values mentioned by Rossi for the various implementations of his circuit. In this new set-up, thanks to the mentioned technique, the important reduction of the resolving time down to approximately 1 μs made it possible to repeat the Rossi's measurement without any lead shield to protect the GMTs from the environmental radioactivity, because the "equivalent shielding" is produced via software through

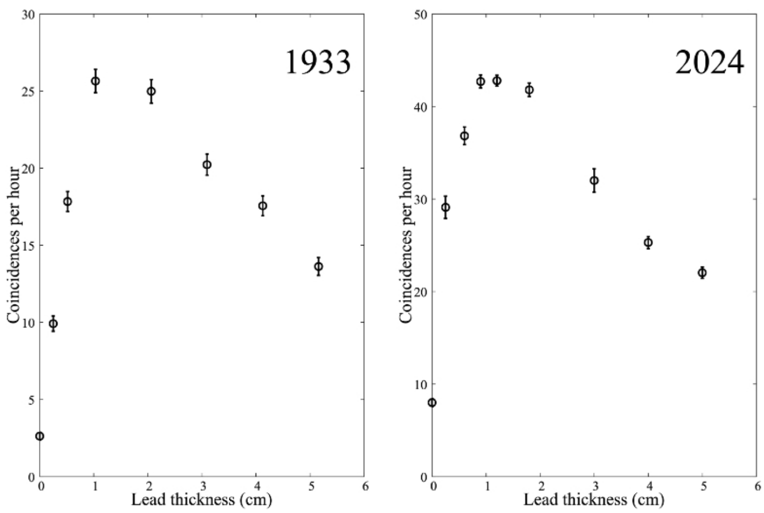

Fig. 5: A comparison between the original Rossi's data and the results of our measurements with the modern apparatus. As expected, the coincidence rates are different: detector size, distance, efficiency are not the same.

the rejection of identified random coincidences falling outside the μs-wide-peak of true coincidences, according to proper selection criteria.

4. Conclusions

The results shown in Fig. 5 show a great similarity with the original results obtained by Rossi in 1932. This achievement from one side confirms that presently available instrumentation (even at relatively low cost) permits to reproduce an experiment which constituted a very important step forward in the understanding of cosmic ray physics; from another, demonstrates once again the impressive ability of Rossi, who had to invent the instrumentation necessary to perform experiments in a field of physics almost totally unexplored and obscure at that time. Further efforts of our group are not excluded, dedicated to implement a simplified setup of the described experiment for installation in didactic laboratories of high school and university.

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