MEASUREMENT OF THE π/p RATIO IN COSMIC RAYS USING THE MOON SHADOW WITH THE L3+C DETECTOR

J.F. PARRIAUD
on behalf of the L3 collaboration
Institut de Physique Nucléaire de Lyon, 4 rue Enrico Fermi,
69622 Villeurbanne, France

The observation of the Moon shadow effect with the L3+C detector is reported. The expected offset and elongation of the Moon shadow due to the geomagnetic field are clearly observed. A determination of the angular resolution and pointing error has been performed through this observation. A preliminary upper limit of the π/p ratio in cosmic rays is given in the TeV region.

1 Introduction

In 1957, Clark proposed the effect of the Moon or the Sun on cosmic rays: as these bodies pass overhead during a transit, they block particles, resulting in shadows in cosmic rays visible by detectors on Earth. The observation of this shadow may be used to check the angular resolution of the apparatus and to evaluate pointing errors. Another use has been proposed in 1990: positively charged particles are deflected by the Earth’s magnetic field towards the East. Consequently their absorption by the Moon gives rise to a shadow on the West side of the Moon. Negatively charged primaries (antimatter) are deviated to the opposite side. A shadow on the East side of the Moon would therefore be observed in presence of antimatter in cosmic rays.

Up to now, no antinuclei heavier than antiprotons have been detected. Antiproton flux measurements have been performed by balloon-borne experiments up to 40 GeV (Figure 1). They are consistent with the antiproton production expected from proton interaction in the interstellar medium: $p + N \rightarrow \overline{p} + X$. However one can notice that the $\overline{p}/p$ ratio measurements are still compatible with an increase expected from an extragalactic component or heavy particle decays in the galaxy. Measurements at higher energies are thus welcome to set constraints on the existence of antimatter in the universe.
A description of the L3+C experiment is given in section 2. In section 3, relevant aspects of the Moon shadow study are detailed. Finally, in section 4, the procedure followed to analyse the data is explained, a preliminary measurement of the $\overline{p}/p$ ratio in the TeV region is performed and a 90% C.L. upper limit is inferred.

2 The L3+C experiment

L3 (Figure 2) was one of the four particle detectors installed on the Large Electron Positron collider (LEP) site, located underneath the French-Swiss border at CERN. It was designed to make a very precise measurement of leptons and photons produced in $e^+e^-$ collisions. In the late 1990s, it was updated to detect cosmic muons originating from the decay of charged pions produced when a high energy cosmic ray collides with an air nucleus.

One of the assets of the L3 detector was its muon spectrometer. It consisted of two octagonally shaped rings, each with eight ”octants”, located in the 1000 m$^3$ magnetic field of 0.5 T created by the solenoid. Each octant contained precision drift chambers organised in 3 layers to measure the projection of the muon trajectory onto the plane orthogonal to the magnetic field, and layers of drift cells to measure the projection along the magnetic field direction. The momentum resolution achieved by this setup was 2.5% at 45 GeV. Other parts of the L3 detector were not used by the L3+C experiment. The reference time $t_0$, when a muon enters the detector, was measured by 202 m$^2$ of additional scintillators covering the upper part of the detector with a 1.5 ns resolution. In order to register events independently of L3 running, new trigger and data acquisition system were made. Since the L3 detector was located under 30 m of molasse, the muon momentum threshold was about 15 GeV and it provided shielding from the electromagnetic and hadronic components of the air showers. In addition to this underground muon detector, an Air Shower (EAS) array of 50 scintillators has been installed at the surface.

The original purpose of L3+C is the measurement of the muon momentum spectrum from 20 to 2000 GeV, which is related to the neutrino flux. Other topics are under study, among which the search for point sources and gamma-ray bursts, where the knowledge of the angular resolution and the pointing error is of primary importance. The study of the Moon shadow will help to determine both quantities in addition to the measurement of the $\overline{p}/p$ ratio at TeV energies in

Figure 1 : $\overline{p}/p$ ratio versus momentum, adapted from reference 5. The lines are calculations of interstellar antiprotons assuming a pure secondary production during the propagation of cosmic rays in the Galaxy. The L3+C experiment is sensitive to a $\overline{p}/p$ ratio at a few % level, for a primary proton energy between 0.5 TeV and 1 TeV.

Figure 2 : The L3 detector. The solenoid, the muon chambers and the scintillator tiles are the main ingredients of the L3+C detector. The subdetectors located inside the support tube are not used.
3 The Moon shadow effect

As already explained in section 1, the Moon shadow effect can be exploited to measure the ratio of antimatter to matter in cosmic rays, using ground-based experiments with Čerenkov detectors, EAS arrays or muon track detectors. The first two methods are sensitive to the total energy of the primary \( E_0 \), so that \( He^4 \) and heavier nuclei participate significantly. Muon experiments are sensitive to the primary energy per nucleon \( E_0/A \), which strongly favours protons so that they measure mostly the \( p/p \) ratio.

The L3+C detector acceptance ranges from zenith angle \( \theta_z = 0^\circ \) to almost \( 60^\circ \) and is given in Figure 3. The apparent position of the Moon is computed with the SLALIB package, taking into account parallax corrections, at any time. The effect of the Earth’s magnetic field has been simulated using the International Geomagnetic Reference Field (IGRF) model. Assuming a proton momentum, the geomagnetic deflection \( \Delta \vec{p} = \vec{p}_{\text{initial}} - \vec{p}_{\text{detected}} \) is computed. It is seen in Figure 3 that both the direction and the amount of deflection undergone by primary particles vary with the position of the Moon. It tends to blur the image of the Moon shadow. A new coordinate system, with axis parallel and orthogonal to the computed deflexion has been defined to minimize this effect and will be referred to as ”deflection coordinate system”.

![Figure 3: The L3+C acceptance.](image)

\( \alpha_z \) and \( \theta_z \) stand respectively for the azimuth and zenith angles. Each pixel corresponds to a direction to the sky. A bipolar structure is observed due to the detector geometry. A transit of the Moon is indicated with dots. For each dot, the geomagnetic deflection is given by an arrow, whose length is proportional to the amount of deflection (see reference arrow in bottom-left corner).

4 Analysis procedure for the Moon shadow

As a first step, the background has been subtracted from the data and a smoothing algorithm applied. Results can be seen in figure 4 for two muon momentum ranges. In the deflection coordinate system, the Moon shadow is observed with a 7\( \sigma \) significance with high energy muons (HE: \( p_\mu \geq 100 \text{ GeV} \), figure 4a) and 4.9\( \sigma \) significance with low energy muons (LE: \( 65 \leq p_\mu \leq 100 \text{ GeV} \), figure 4b). It is aligned along the horizontal axis as expected. Both the offset and the elongation due to the geomagnetic field are observed, with a more pronounced effect for low energy muons as expected. Comparing the observed offset to the expected one (MC), the pointing error is deduced to be less than 0.1\(^\circ\). From Figure 4c, an effective angular resolution of 0.43\(^\circ\) ± 0.05 is deduced for the whole muon sample, including the geomagnetic field effect. A determination of the effective angular resolution without the geomagnetic field effect is performed by projecting both two-dimensional plots on the vertical axis, where the geomagnetic field effect is minimized. This characteristic of the deflection coordinate system allows to extract angular resolution values of 0.22\(^\circ\) ± 0.05 and 0.30\(^\circ\) ± 0.07 respectively for HE and LE muon samples.

A maximum likelihood fit has been performed on data in the deflection coordinate system with all muons with momentum greater than 65 GeV (HE + LE), assuming that the data can be
described as a planar background and 2 symmetric Gaussian deficits for protons and antiprotons:

$$f(x, y) = ax + by + c - \frac{N}{1 + r [F_p(x_0, y_0, \sigma)]} + \frac{r}{p/\rho \text{ ratio}} [F_p(-x_0, -y_0, \sigma)],$$

where parameters $x_0$ and $y_0$ express the offset due to the geomagnetic field. Uncertainties on parameters have been computed with a Monte Carlo simulation. A deficit of 944 ± 320 events is reported with 8σ significance. A preliminary $p/\rho$ ratio measurement is obtained: $r = -0.14 \pm 0.15$. An upper limit has been set at 0.13 with 90% C.L. using the “unified approach”.

5 Conclusion

The L3+C experiment is not only one more experiment to observe a significant Moon shadow effect. Its good angular resolution has allowed for the first time to observe clearly the offset and the elongation of the Moon “muon shadow” expected from the geomagnetic field for 2 different muon energy ranges. Moreover, it allows a better separation of the proton and antiproton deficits. A preliminary measurement of the $p/\rho$ ratio yields an upper limit of 0.13 at 90% C.L. for the muon sample with $E_\mu \geq 65$ GeV.

This analysis is still preliminary since only one third of the data has been reconstructed up to now. A complete reconstruction of the data is on the way. Improvements are also expected from a better description of the deficit and determination of the angular resolution from the study of dimuon events.

References

1. G.W. Clark, *Phys. Rev.* D **108**, 450 (1957).
2. M. Urban, *et al.*, *Nucl. Phys.* B **14**, 223 (1990).
3. L. Bergström, J. Edsjö and P. Ullio, *Astrophys. J.* **526**, 215 (1999).
4. L3+C detector: O. Adriani, *et al.*, *Nucl. Instrum. Methods* A **488**, 209 (2002).
5. M. Boezio, *et al.*, *Astrophys. J.* **561**, 787 (2001).
6. SLALIB — Positional Astronomy Library, Starlink User Note 67, P. T. Wallace, 6 September 2001.
7. G. Feldman and R. Cousins, *Phys. Rev.* D **57**, 7 (1998).