Looking at cosmic rays with accelerator detectors

Large detectors constructed at accelerator labs can also be used in parallel for cosmic-ray studies. Effects measured in distant detectors could be correlated to provide a broader view of particles from the cosmos.

When CERN came into being in the early 1950s, a sea change was taking place in particle physics research. Until then, cosmic rays had provided most of the basic particle physics discoveries. Accelerators made their first contributions at Berkeley in 1949, with the Chicago and Carnegie synchrocyclotrons not far behind. In 1953, the Cosmotron, so named because it was the first accelerator to attain cosmic-ray energies, began operation at Brookhaven and provided physicists with the first laboratory-made strange particles.

At the Bagneres conference in 1953, leading cosmic-ray physicist Cecil Powell, who had been awarded the 1950 Nobel Prize for his 1947 discovery of the pion, said: “We have been invaded. The accelerators are here.”

Although many of CERN’s first-generation physicists cut their research teeth on cosmic rays, for more than 40 years CERN went about building and exploiting its large accelerators, and cosmic-ray physics took a back seat.

With cosmic rays reporting particles beyond $10^{20}$ eV – thousands of times as high as the highest laboratory energies now available – particle physicists are rediscovering the attractions of natural sources of high-energy particles. While these natural sources provide energies far beyond those that will be opened up by the next generation of particle colliders, the event rates are puny in comparison.

Cosmic-ray revival

There are two primary motivations for this cosmic-ray revival. First, dramatic results from the Super-Kamiokande underground experiment in Japan, studying neutrinos produced by cosmic-ray collisions in the atmosphere, strongly suggest that the different kinds of neutrinos transform into each other – or “oscillate”. To exploit these neutrino possibilities fully requires accurate knowledge of the cosmic-ray muon spectrum. With existing data samples mutually disagreeing by 20–30%, more accurate data are called for.

Second, direct measurements of primary cosmic rays of energies of greater than $10^{14}$ eV (100 TeV) are impractical. For example, above $10^{18}$ eV there is only one particle per square metre per steradian per year. However, the primary cosmic-energy spectrum extends beyond $10^{20}$ eV and there is great interest in the composition, the energy spectrum and the interaction of the primary cosmic rays with nuclei in the upper atmosphere. Knowledge of the cosmic-particle composition above the “knee” (a few times $10^{15}$ eV) could shed light on how particles are accelerated to such high energies.
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From ground-based observations of different particles (in extensive air showers) and from studies of atmospheric scintillation and Cherenkov light, the cosmic-ray community has learned a lot, but many mysteries and uncertainties remain. Even with good data, it is difficult to determine simultaneously a unique primary composition and interaction model.

Data collected by large detectors at accelerator laboratories would be a valuable contribution. With a relatively modest investment, these detectors can be exploited for cosmic-ray physics in parallel with, and with no loss in efficiency for, the primary mission.

At CERN's LEP collider, a subgroup of the L3 collaboration has formed the L3+Cosmics group, using new electronics to enable the muon spectrometer drift chambers to be read out independently of LEP data collection. A blanket of about 200 sq. m of scintillator has been installed over the top three octants of the magnet to provide a reference time signal for cosmic-ray data collection. Under 30 m of rock, the cosmic-ray muon threshold for L3 is about 15 GeV.

Elsewhere in the LEP ring, members of the ALEPH collaboration are running a pilot CosmoALEPH experiment to look for coincident muons over long distances. This group has examined, together with the newly established CosmicLEP group, the cosmic-ray data collected during the ALEPH runs.

Data archives have revealed a substantial collection of cosmic-ray muon events. Although the detector is live for only 10% of the time for cosmic-ray particles, this nevertheless adds up over several years to more than a million seconds (about 12 days).

Muon multiplicities, etc., have been analysed using sophisticated cosmic-ray simulation programs developed by the Karlsruhe group. Intriguing events, producing unprecedented numbers of muons, have sparked a proposal to study these phenomena in more detail.

Topical workshop

A topical workshop in Sodankyla, about 100 km north of the Arctic Circle in Finland, on 24–29 April and organized by Karsten Eggert of CERN, highlighted the resurgence of interest in cosmic-ray muons.

The Karlsruhe group with its KASCADE detector array has, perhaps, the most comprehensive data so far on ground-level air showers, which can be interpreted in terms of the primary cosmic-ray spectrum and its composition.

C Taylor (Case Western Reserve) and R Engel (Bartol) looked at the primary cosmic-ray nuclear interaction, noting the uncertainty in the final state particle production at very small forward angles that dominates cosmic-ray muon production.

Even though Fermilab's Tevatron Collider energy corresponds to a cosmic ray, of about $2 \times 10^{18}$ eV, interacting with an air nucleon at rest, there are almost no data on forward particle production at energies above the older fixed-target experiments at a few hundred giga electron-volts.

ALEPH and L3 surveyed their respective cosmic-ray muon observations. H Wilkens (Nijmegen) gave an update on the additions to the L3 detector and electronics and the muon programme in progress. S Tonwar (Tata Institute) described the planned addition of a surface air shower array above L3, which will enable the observation of energetic muons together with the related air shower.

J Strom (Arcada), A Bruhl (Siegen) and M Schmelling (Max-Planck Institute) presented the current status of the ALEPH cosmic-ray programme. More than 300 000 cosmic-ray muon events have been analysed, and good agreement with the KASCADE Monte Carlo simulations obtained for multimuon events observed in the 16 sq. m time-projection chamber for multiplicities (total number of produced particles) between 2 and 40. However, there are five events with unexpectedly large multiplicities: up to 150 (in some cases with additional muons observed in the hadron calorimeter).

Other ALEPH studies look at the "decoherence" curve – the coincidence rate between two muon detectors as a function of their separation, extending beyond 1 km.

Horst Wachsmuth (CERN) proposed looking for muon coincidences between the four LEP detectors, a phenomenon that should not occur for any "ordinary" cosmic-ray interaction in the Earth's upper atmosphere. Such a coincidence, suggested by some earlier cosmic-ray experiments, would certainly require explanation.

Other major particle physics detector groups are also interested. A De Roeck (DESY) discussed the potential involvement of the big H1 and ZEUS detectors at DESY's HERA electron-proton collider for studies of coincident cosmic-ray muons. With these detectors only 3 m below ground they could study cosmic-ray muons down to energies of 2 or 3 GeV, which is of great interest to the atmospheric muon neutrino groups.

It is also possible, using satellite (GPS) time recording, to look for time correlations between cosmic-ray muons at DESY and CERN.

Future study

M Vallinkoski (Oulu) described a possible new cosmic-ray muon experiment in a mine in Phyhasalmi, Finland. The Centre for Underground Physics in Phyhasalmi (CUPP) would deploy a seven-detector array at several vertically aligned depths to study the multiplicity, lateral distribution and energy spectrum of cosmic-ray muons.

It was noted that major detectors could also be sensitive to point sources of cosmic-ray muons and, using the Moon as a cheap and efficient absorber and the Earth's magnetic field as a spectrometer, might set a limit on the relative flux of high-energy primary antimatter nuclei.

The Chinese IHEP group is particularly interested in seeking evidence for possible cosmic-ray associated weakly interacting massive particles (WIMPs) in L3.

Workshop organizer Karsten Eggert discussed other areas of future study, including working with larger and upgraded detectors. As noted by Lawrence Jones (Michigan) in his opening discussion, muon studies with LEP detectors contain both elements of an ideal experimental programme: practical and useful results, such as the absolute inclusive muon spectrum, while at the same time there is sensitivity to new and potentially exciting discoveries, such as unexpected muon multiplicities, cosmic-ray point sources, WIMP discoveries and statistically significant coincidences. Paolo Lepri of Rome summarized the attractions of the proposed new programme.
ALEPH experiments go cosmic

Designed to study man-made electron-positron collisions in CERN’s LEP ring, the ALEPH detector is also ideal for observing complicated natural cosmic-ray events.

High-energy primary cosmic-ray particles crashing into the atmosphere 20 km above our heads initiate large air showers with hadrons, electrons, muons and neutrinos. By the time they reach ALEPH, 125 m underground, all of these particles are absorbed except for neutrinos and muons above 70 GeV.

ALEPH provides high resolution tracking in its central Time Projection Chamber (TPC) in a solenoidal magnetic field and the large hadron calorimeter surrounding the TPC provides further information about cosmic muons.

Precision study of these muons, in particular of muon bundles, gives vital information about the primary cosmic rays and the way in which shower particles are produced in the very forward (downward) direction. The primary cosmic particle composition around the "knee" of the energy spectrum ($4 \times 10^{15}$ eV) is fundamental input for understanding the cosmic acceleration mechanism that pushes particles to these energies.

After analysing cosmic muon events captured by ALEPH in parallel with LEP data-taking and during a special one-week cosmic run, five events were found with the highest muon density ever seen. Some 100 muons hit the sensitive area ($16 \, m^2$) of the ALEPH TPC. The most crowded event showed about 160 muons in half of the TPC, the other half suffering data overflow.

Extensive simulations using the Corsika program, which was developed by the Karlsruhe group, reproduce the lower muon multiplicities, assuming a primary cosmic particle composition ranging from protons up to nuclei like iron. However, the five spectacular events are an order of magnitude above the simulation prediction. They could come from either unusually large air showers, above $10^{17}$ eV, or fluctuations from lower-energy showers, which could hint at new mechanisms for forward particle production.

Charge and momentum determination of the muons in these events, as well as the study of their structure over larger areas, may shed light on their origin. A special cosmic run of ALEPH using the tracking hadron calorimeter extended muon measurements to cover $50 \, m^2$. The largest event from this run produced more than 100 muons.

High-multiplicity events

To study these intriguing events the CosmoLEP group proposes placing a 200 $m^2$ array of drift chambers beside the ALEPH experiment. With this large array, the rate of high multiplicity events would be increased by a factor of more than a hundred and the muon patterns would give a window on the energy and composition of the primary cosmic particles. The larger samples could also reveal point sources of cosmic particles in the depths of the universe.

The underground muon showers that have been seen so far extend over, at most, a few hundred metres. The CosmoALEPH effort covers the barrel of ALEPH’s central hadron calorimeter together with several scintillator counter stations installed around the LEP ring near ALEPH, which are up to about 1 km distant. This pilot experiment saw coincident muons in counters that were several hundred metres apart and triggered an idea for a still wider muon search.

The four LEP experiments, equally spaced around the 27 km tunnel, could look for muon correlations over much larger distances. The same approach is being followed at the H1 and ZEUS detectors at the HERA collider at DESY in Hamburg, which are approximately 2 km apart.
COSMIC RAYS

L3+C = new tool set to study cosmic-ray muons

Also under way at CERN is the L3 experiment at LEP, which has installed a 200 sq. m screen of scintillator to intercept cosmic rays arriving from the atmosphere.

L3+C, an offshoot of the L3 experiment at CERN’s LEP electron–positron collider, has been a “recognized” experiment at CERN since April 1998. It takes advantage of the unique properties of the big L3 muon spectrometer (low energy threshold compared to other underground detectors and unrivalled momentum resolution over a wide momentum range) for accurate measurements of cosmic-ray muons penetrating 30 m underground.

A new muon trigger, readout and data acquisition system have been installed, as well as a 204 sq. m scintillator matrix covering the L3 magnet to time the passage of particles. Data are collected independently, in parallel with L3 running at LEP.

New results for a variety of fundamental topics in cosmic rays, astrophysics and particle physics are expected. The cosmic-ray muon momentum spectrum, zenith angular dependence and charge
COSMIC RAYS

ratio are being measured to 1% between 10 and 2000 GeV, thanks to L3’s muon drift chambers and large magnetic volume.

The results will provide new information on the primary composition of cosmic rays, shower development in the atmosphere, and pion and kaon levels at high energies. These data will also help us to understand the “atmospheric neutrino puzzle”, where an anomalous muon neutrino signal seen by underground neutrino detectors is heralded as an indication of neutrino oscillations. In particular, the precision measurements will allow a prediction of the absolute number of upward-moving, through-going muons above 10 GeV observed by Super-Kamiokande and MACRO underground.

L3+C started gathering data in 1998. Then in early 1999 it increased its acceptance considerably, achieving an event rate of 550 Hz. In addition to providing more reliable data, this extends both the momentum measurement and the angular range.

The detector could reveal bursts of point source signals, and eventually gamma-ray bursts, and analyse their associated muons. The absence of high energy, upward-moving muons (above a few hundred giga electron-volts) will allow a limit to be set on the neutrino flux from active galactic nuclei. Studies of the primary composition of cosmic rays in the “knee” region (near $10^{15}$ eV) will be boosted in a unique way by recording muon “families” and measuring all of their momenta. With exotic events recorded by many different experiments, particle momentum spectra should reveal clues to the processes involved.

The detector will also intercept some upward muons (due to particles that have traversed the Earth). Time variations could reveal meteorological or sidereal effects. Correlations with events seen by other detectors are also among L3+C’s experimental objectives.

Observing the Moon’s muon shadow may give a flux limit of primary antiprotons near 1 TeV - the Earth’s magnetic field acting as a convenient momentum analyser and the Moon as an absorber of cosmic particles.

**Independent apparatus**

The collaboration is preparing to install 50 scintillators below the roof of the L3 access hall (above ground). This air shower array will help to estimate the primary energy of some showers associated with the muons measured underneath. This apparatus is completely independent and runs by itself. Events are correlated via the GPS satellite clock and a signal in the data acquisition system.

L3+C experiment already has collected some 900 million events and is expected to run up to the end of the LEP operation period next year. The first data were presented at August’s International Cosmic-Ray Conference in Salt Lake City.

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