SOCIETÀ ITALIANA DI FISICA

PROCEEDINGS
OF THE
INTERNATIONAL SCHOOL OF PHYSICS
«ENRICO FERMI»

COURSE CLXXV

Radiation and Particle Detectors

SOCIETÀ ITALIANA DI FISICA BOLOGNA-ITALY

ITALIAN PHYSICAL SOCIETY

PROCEEDINGS

OF THE

INTERNATIONAL SCHOOL OF PHYSICS

"ENRICO FERMI"

COURSE CLXXV

edited by S. BERTOLUCCI and U. BOTTIGLI

Directors of the Course

and

P. OLIVA

VARENNA ON LAKE COMO

VILLA MONASTERO

20 – 25 July 2009

Radiation and Particle Detectors

2010

IOS Press

AMSTERDAM, OXFORD, TOKIO, WASHINGTON DC

ISSN 0074-784X (print)
ISSN 1879-8195 (online)

ISBN 978-1-60750-630-0 (print) (IOS Press)
ISBN 978-1-60750-631-7 (online) (IOS Press)
ISBN 978-88-7438-058-9 (SIF)

LCCN 2010934193

Production Manager
A. Oleandri

Copy Editor
M. Missiroli

jointly published and distributed by:

IOS PRESS
Nieuwe Hemweg 6B
1013 BG Amsterdam
The Netherlands
fax: +31 20 687 0019
info@iopress.nl

SOCIETÀ ITALIANA DI FISICA
Via Saragozza 12
40123 Bologna
Italy
fax: +39 051 581340
order@sif.it

Distributor in the USA and Canada
IOS Press, Inc.
4502 Rachael Manor Drive
Fairfax, VA 22032
USA
fax: +1 703 323 3668
sales@iospress.com

SOCIETÀ ITALIANA DI FISICA

RENDICONTI
DELLA
SCUOLA INTERNAZIONALE DI FISICA
"ENRICO FERMI"

CLXXV CORSO

a cura di S. BERTOLUCCI e U. BOTTIGLI
Direttori del Corso
e di
P. OLIVA

VARENNA SUL LAGO DI COMO
VILLA MONASTERO
20 – 25 Luglio 2009

Rivelatori per radiazione e particelle

2010

SOCIETÀ ITALIANA DI FISICA
BOLOGNA-ITALY

Supported by

Istituto Nazionale di Fisica Nucleare (INFN)

INFN, Sezione di Pisa

Preface

From the 20th to 25th of July 2009 the International School of Physics entitled "Radiation and Particle Detectors" was held in Varenna, which involved the use of detectors for the research in fundamental physics, astro-particle physics, and applied physics. At the school ten teachers and thirty students were present.

In the context of fundamental physics the High Energy Physics (HEP) plays an important role. In general the HEP experiments make use of sophisticated and massive arrays of detectors to analyze the particles which are produced in high-energy scattering events. This aim can be achieved in a large variety of approaches. Some examples are the following:

- Measuring the position and length of ionization trails. Much of the detection depends upon ionization.
- Measuring time of flight permits velocity measurements.
- Measuring radius of curvature after bending the paths of charged particles with magnetic fields permits measurement of momentum.
- Detecting Cherenkov radiation gives some information about energy, mass.
- Measuring the coherent "transition radiation" for particles moving into a different medium.
- Measuring synchrotron radiation for the lighter charged particles when their paths are bent.
- Detecting neutrinos by steps in the decay schemes which are "not there", *i.e.*, using conservation of momentum, etc. to imply the presence of undetected neutrinos.
- Measuring the electromagnetic showers produced by electrons and photons by calorimetric methods.

- Measuring nuclear cascades produced by hadrons in massive steel detectors which use calorimetry to characterize the particles.

- Detecting muons by the fact that they penetrate all the calorimetric detectors.

All these types of detectors are used in the largest accelerator ever built: the Large Hadron Collider (LHC). LHC is a proton-proton (also ions) ring, 27 km long, 100 m underground, with 1232 superconducting dipoles 15 m long at 1.9 K producing a magnetic field of 8.33 T. The figures of merit, for proton-proton operations, are beam-energy 7 TeV ($7\times$ TEVATRON), luminosity $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ ($> 100\times$ TEVATRON), bunch spacing 24.95 ns, particles/bunch $1.1\cdot 10^{11}$, and stored emergy/beam 350 MJ. For ion-ion operations we will have energy/nucleon 2.76 TeV/u, and total initial luminosity of $10^{27}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The main four experiments are two general purpose experiments (ATLAS and CMS), B-physics and CP violation experiment (LHCB), and heavy ions experiment (ALICE).

The international community of physicists hopes that the LHC will help answer many of the most fundamental questions in physics: questions concerning the basic laws governing the interactions and forces among the elementary particles, the deep structure of space and time, especially regarding the intersection of quantum mechanics and cosmology, where current theories and knowledge are unclear or break down altogether. The enormous success of the Standard Model (SM), tested at per mil level with all particles discovered except the Higgs boson, will hopefully be able to build a Cosmology Standard Model.

The issues of LHC physics include, at least:

- Is the Higgs mechanism for generating elementary particles masses via electroweak symmetry breaking indeed realised in nature? It is anticipated that the collider will either demonstrate or rule out the existence of the elusive Higgs boson, completing (or refuting) the SM.

- Is supersymmetry, an extension of the SM and Poincaré symmetry, realised in nature, implying that all known particles have supersimmetric partners?

- Are there extra-dimensions, as predicted by various models inspired by string theory, and can we detect them?

- What is the nature of the Dark Matter which appears to account for 23% of the mass of the universe?

Other questions are:

- Are electromagnetism, the strong force, and the weak interaction just different manifestations of a single unified force, as predicted by various Grand Unification Theories (GUTs)?

- Why is gravity so many orders of magnitude weaker than the other three fundamental interctions (Hierarchy Problem)? For all proposed solutions: new particles should appear at TeV scale or below.

- Are there additional sources of quark flavours, beyond those already predicted within the Standard Model?

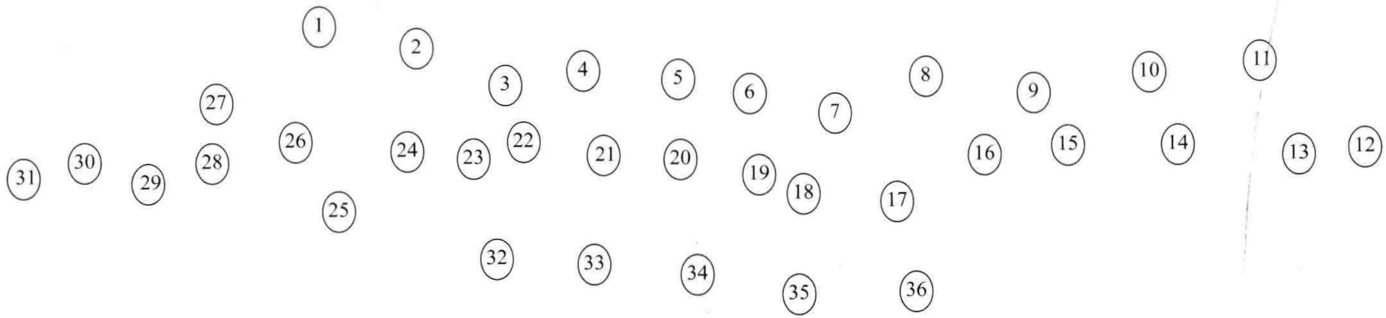
- Why are there apparent violations of the symmetry between matter and antimatter (CP violation)?

- What was the nature of the quark-gluon plasma in the early universe (ALICE experiment)?

Obviously, for the construction of a Standard Cosmology Model, the astro-particle experiments are crucial with direct or indirect dark matter measurements. In particular, the Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) experiment, which went into space on a Russian satellite launched from the Baikonur cosmodrome in June 2006, uses a spectrometer —based on a permanent magnet coupled to a calorimeter— to determine the energy spectra of cosmic electrons, positrons, antiprotons and light nuclei. The experiment is a collaboration between several Italian institutes with additional participation from Germany, Russia and Sweden. PAMELA represents a state of the art of the investigation of the cosmic radiation, addressing the most compelling issues facing astrophysics and cosmology: the nature of the dark matter that pervades the universe, the apparent absence of cosmological antimatter, the origin and evolution of matter in the Galaxy. PAMELA, a powerful particle identifier using a permanent magnet spectrometer with a variety of specialized detectors, is an instrument of extraordinary scientific potential that is measuring with unprecedented precision and sensitivity the abundance and energy spectra of cosmic rays electrons, positrons, antiprotons and light nuclei over a very large range of energy from 50 MeV to hundreds GeV, depending on the species. These measurements, together with the complementary electromagnetic radiation observation that will be carried out by AGILE and GLAST space missions, will help to unravel the mysteries of the most energetic processes known in the universe. Recently published results from the PAMELA experiment have shown conclusive evidence of a cosmic-positron abundance in the 1.5–100 GeV range. This high-energy excess, which they identify with statistics that are better than previous observations, could arise from nearby pulsars or dark matter annihilation. Such a signal is generally expected from dark matter annihilations. However, the hard positron spectrum and large amplitude are difficult to achieve in most conventional WIMP models. The absence of any associated excess in antiprotons is highly constraining on any model with hadronic annihilation modes. The light boson naturally provides a mechanism by which large cross-sections can be achieved through the Sommerfeld enhancement, as was recently proposed. Depending on the mass of the WIMP, the rise may continue above 300 GeV, the extent of PAMELA's ability to discriminate electrons and positrons. The data presented include more than a thousand million triggers collected between July 2006 and February 2008. Fine tuning of the particle identification allowed the team to reject 99.9% of the protons, while selecting more than 95% of the electrons and positrons. The resulting spectrum of the positron abundance relative to the sum of electrons and positrons represents the highest statistics to date. Below 5 GeV, the obtained spectrum is significantly lower than previously measured. This discrepancy is believed to arise from modulation of the cosmic rays induced by the strength of the solar wind, which changes periodically through the solar cycle. At higher energies the new data unambiguously confirm the rising trend of the positron fraction, which was suggested by previous measurements. This appears highly incompatible with the usual scenario in which positrons are produced by cosmic-ray nuclei interacting with atoms in the interstellar medium. The additional source of positrons dominating at the higher energies could be the signature of dark matter decay or annihilation. In this case, PAMELA has already shown that dark matter would have a preference for leptonic final states. They suggest that the alternative origin of the positron excess at high energies is particle acceleration in the magnetosphere of nearby pulsars producing electromagnetic cascades. The members of the collaboration state that the PAMELA results presented here are insufficient to distinguish between the two possibilities. They seem, however, confident that various positron production scenarios will soon be testable. This will be possible once additional PAMELA results on electrons, protons and light nuclei are published in the near future, together with the extension of the positron spectrum up to 300 GeV thanks to ongoing data acquisition.

S. BERTOLUCCI, U. BOTTIGLI and P. OLIVA

Società Italiana di Fisica
SCUOLA INTERNAZIONALE DI FISICA «E. FERMI»
CLXXV CORSO - VARENNA SUL LAGO DI COMO
VILLA MONASTERO 20 - 25 Luglio 2009



1) A. Agostinelli
2) D. Caffarri
3) A. Junkes
4) F. Bellini
5) B. Guerzoni
6) V. Cavaliere
7) L. Caforio
8) A. Silenzi
9) M. Siciliano
10) D. Fasanella
11) M. Nocente
12) M. Bettuzzi
13) P. Allegrini
14) P. Bennati
15) A. Di Canto
16) F. Sforza
17) M. V. Siciliano
18) F. Albertin
19) P. Garosi
20) G. Volpe
21) L. Velardi
22) J. Lange
23) D. Lattanzi
24) L. Soung Yee
25) E. Gurpinar
26) G. Sabatino
27) M. Endrizzi
28) S. Tangaro
29) B. Alzani
30) R. Brigatti
31) L. Strolin
32) P. Oliva
33) J. Marque
34) M. Mulders
35) U. Bottigli
36) G. Riccobene

Detectors for medical physics

Notes from the lecture of Maria Giuseppina Bisogni

Università di Pisa, Dipartimento di Fisica "E. Fermi"
and INFN Sezione di Pisa - Pisa, Italy

A straightforward application of detection technologies developed in high-energy physics is medical imaging.

Two main fields of medical imaging have to be covered by these detectors: morphological imaging and functional imaging. And the most used radiation type are X-rays or gamma rays.

Since the beginning of morphological imaging the most used detector has been the screen-film system. However, in the recent years digital detectors have become more and more important. Digital imaging has several advantages with respect to conventional imaging: the images can be displayed, stored and processed by a computer and can be easily transferred from one site to another. Moreover digital detectors have a wider dynamic range so the exposure is a less critical factor.

Digital detection can be performed in a direct on in an indirect way: in the first case the radiation interacts directly with the detector, while in the second case it interacts with a scintillator and the light produced in it is then detected by the digital detector.

A first example of digital detectors for medical imaging are Charge Coupled Devices (CCD). They are based on the technology Metal Oxide Semiconductor (MOS). The charge produced is stored in a potential well. The potential changes to make the charges shift from one pixel to the next in a given column and there is a serial read-out with a clock.

CCDs are generally coupled to scintillators CsI(Tl) to improve efficiency, so they are indirect digital detectors.

Widely used indirect digital detectors are a-Si Flat Panels. They are made of a-Si:H photodiodes (low dark current, high sensitivity to green light), coupled to CsI phosphors. In order to improve efficiency by keeping spatial resolution high, the scintillator is made of CsI:Tl needle crystals: their thickness is about $550\,\mu$m, which allows a good X-ray absorption. The needles act as light guides, leading to a sharp point spread function. Moreover CsI:Tl emits green light.

Examples of direct digital detection are a-Se Flat Panels. They are made of alloyed a-Se with % As and with ppm Cl and the detection system is a TFT.

A challenging application of these detectors is digital mammography. In mammography the details of interest are very low contrast ones (like tumor masses) or very small details (like microcalcifications). So mammography is a demanding task for both efficiency and spatial resolution.

A widely used indirect detection system is the GE Senographe 2000D that uses a Flat Panel Digital Detector Si +CsI(Tl).

The total area covered by the detector is $18 \times 24\,\text{cm}^2$ and the pixel is $100 \times 100\,\mu\text{m}^2$.

Nowadays also direct digital detectors are available (a-Se based flat panels) like SeleniaTM, LORAD-Hologic, Mammomat NovationDR Siemens.

A promising alternative to conventional integrating detectors are Single Photon Counting (SPC) Systems. They allow efficient noise suppression, leading to a higher SNR or lower dose, so they are particularly suited for low-event-rate applications.

They are linear whit exposure and have wider dynamic range (with respect to integration detectors), limited only by counter saturation.

They can allow an energy discrimination rejecting Compton events or X-ray fluorescences.

Also "energy weighting" (low-energy photons weight less than high-energy ones in integrating systems) is suppressed because in SPC systems all photons have the same weight.

Sectra MicroDose is the First SPC commercial mammographic system.

The SYRMEP Project (INFN GV, early '90s) also developed an SPC detector. It is an Edge-on Si strip detector. A silicon microstrip detector is used in the so-called "edge-on" geometry matching the laminar geometry of the beam. The absorption length seen by the impinging radiation is given by the strip length ($\sim 100\%$ in 1 cm of silicon for 20 keV photons). There is almost complete scattering rejection. The pixel size is determined by the strip pitch (H) times the detector thickness (V). A drawback is that the dead volume in front of the strip reduces the efficiency of the detector.

The Integrated Mammographic Imaging Project (IMI) is a collaboration between national universities, INFN and Industry which developed a mammography system demonstrator based on GaAs pixel detectors. Photoelectric interaction probability is about 100% in the mammographic energy range (10–30 keV) for a $200\,\mu\text{m}$ thick GaAs crystal.

So the detector is made of $200\,\mu\text{m}$ thick GaAs bump-bonded to a Photon Counting Chip (PCC). The detection unit presents a $18 \times 24\,\text{cm}^2$ exposure field. A 1D scanning is performed by 9×2 assemblies in 26 exposures and the image is "off-line" reconstructed.

Another application of growing interest in medical imaging is the Computed Tomography (CT). This imaging modality is intrinsically related to digital detector, since slice images have to be reconstructed from actually acquired projection images by a specific algorithm.

Current CTs are spiral CT, that acquire the whole volume of interest in a single exposure by rotating continuously both the source and the detectors while the patient is moving along his axial direction. By using multiple arrays of detectors it is now possible to acquire more than one slice simultaneously. Modern systems can acquire up to 256 different slices at the same time. The future of CT is the cone beam CT with a full area detector, which will allow acquisition of large areas in a very small time.

Micro Computed Tomography is a technique for small fields of measurement (typically 5–50 mm). It is characterized by very-low-power X-ray sources (typically 5–50 W) and long scan times (typically 5–30 minutes). It is devoted to the imaging of a specific organ (bone, teeth, vessels, cancer) or to the imaging of samples (biopsies, excised materials) or small animals (rats/mice) *in vivo*, *ex vivo* or *in vitro*.

Functional imaging is dedicated to the *in vitro* or *in vivo* measure of the intensity of functional/metabolic processes occurring within a living body. Nuclear medicine uses molecules or drugs marked with radioisotopes (radiotracer) for this kind of imaging.

The principle of radiotracer applications is that changing an atom in a molecule for its radioisotope will not change its chemical and biological behavior significantly. As a consequence, the movement, distribution, concentration of the molecule can be measured by radiation detectors.

The two main imaging modalities used in nuclear medicine are SPECT (Single Photon Emission CT) and PET (Positron Emission Tomography).

In SPECT the radiotracer emits one photon (for example ^{99m}Tc, while in PET two anticollinear photons are emitted by positron annihilation.

The main detector used in SPECT is the Gamma Camera, that is made of a Pb collimator (that encodes the spatial information), a NaI (Tl) scintillation crystal and an array of PMTs connected to amplifiers and positional logic circuits.

The principle is that many photomultiplier tubes "see" the same large scintillation crystal; an electronic circuit decodes the coordinates of each event.

γ-rays (typically: 140 keV from ^{99m}Tc) are emitted in all directions hence collimators are required to determine the line of response. To perform a CT, in SPECT scanners rotate around the patient.

In PET a tracer containing a β^+ emitting isotope is used. The emitted positron annihilates in a short range (~ 1 mm) emitting two antiparallel photons of 511 keV.

The signal detection is based on the coincidence detection at 180°, leading to a higher sensitivity and a better signal/noise ratio than SPECT.

Detectors are usually scintillators coupled to a read-out device (typically a photomultiplier, PMT), which can be arranged in a ring geometry or in a parallel-plate geometry.

Detectors are usually scintillators: the most often used is BGO (bismuth germanate, $Bi_4Ge_3O_{12}$) and more recently LSO (lutetium oxi-orto silicate, LuSiO).

In a block detector conventionally used in PET, a 2D array of crystals is attached to 4 PMTs. Usually the array will be cut from a single crystal and the cuts filled with light-reflecting material. When a photon is incident on one of the crystals, the resultant light is shared by all 4 PMTs. Information on the position of the detecting crystal may be obtained from the PMT outputs comparing them to pre-set values.

For more than 80 years, the PMT is the photodetector of choice to convert scintillation photons into electrical signals in most of the applications related to the radiation detection. This is due to its high gain, low noise and fast response. Research is now moving to solid-state photodetectors that show the following advantages with respect to PMTs:

- Compactness
- High quantum efficiency (to provide an energy resolution comparable to PMTs)
- Insensitivity to magnetic fields (PET/MRI)

TOF-PET (Time-of-Flight PET) systems exploit the time difference between the two emitted photons to better locate the annihilation position. The limit in the annihilation point location is mainly due to the error in the time difference measurement, namely the time resolution Δt of the coincidence system. Time resolution is used by the reconstruction algorithm to locate the annihilation point Δx ($\Delta x = c\Delta t/2$).

Extensive work on TOF PET was done in the '80s and several TOF PET cameras were built and most of the advantages described here were experimentally verified.

But the scintillator materials used in the '80s (BaF_2 and CsF) had drawbacks (*e.g.*, low density, low photofraction) which required other performance compromises, so BGO dominated PET. Nowadays new scintillating materials like LSO ($\sim 200\,\text{ps}$) and $LaBr_3$ ($< 100\,\text{ps}$) can provide outstanding timing resolution without other performance compromises, so TOF PET is experiencing a rebirth.

Simultaneous PET-CT systems are now available. PET needs CT data to anatomically locate the tumor and to correct for the attenuation in order to provide a correct quantification. Present systems exploit multislice CT top quality systems, where the number of slices can reach 128 with rotation time of the order of 300 ms. Being the attenuation coefficients (μ) energy dependent, the CT scanning at an average energy of 70 keV must be rescaled (voxel by voxel) to the gamma rays by using a bi-linear scaling function.

Synchronization of PET-CT acquisitions with breath cycle minimizes motion effects but limits the data statistics thus ultimately increasing the noise in the final image. The use of non-rigid registrations (NRR) among gated-PET images leads to high-quality, low-noise motion-free PET images.

An interesting alternative to PET-CT systems are PET-MR (PET and Magnetic Resonance) systems which allow to combine function (PET) and anatomy and function (MR). However there are technical challenges in realizing PET/MR systems. There is interference on PET photomultiplier and electronics due to the static magnetic field and to the RF and the gradient fields. There are also interferences on MR homogeneity and gradients due to electromagnetic radiation from PET electronics, in maintaining magnetic-field homogeneity. Moreover PET attenuation correction via MR data is a challenge.

Regarding the optimal detection system for PET in PET-MR systems, two different approaches are under investigation: scintillating crystals plus photomultiplier tubes (PMT) or scintillating crystals plus solid-state light detectors. PMTs are well understood, have stable electronics and high gain (10^6). However, Position Sensitive PMT

(PSPMT) operate in magnetic fields of 1 mT. A combination of distance (light guide) and iron shield (1–2 mm of soft iron can further reduce 30 mT $\rightarrow$ 1 mT) is used to allow PSPMT to operate in 1 mT. 1 mT has minimal effect on PSPMT performance. However long light guides reduce the energy resolution from 17 to 27%, but this should not have too big an impact upon performance. Simultaneous and isocentric MR/PET measurements can be performed. However, this system presents a small axial field of view (FOV).

The alternative to PMTs are solid-state devices, like Avalanche Photodiodes (gain ~ 150), Silicon Photomultiplier (gain $\sim 10^6$). They are less well established than PET detectors, but can operate in high static field greater than 7 T. However, there is still the need to shield devices from both gradients and RF.

P. OLIVA

INDICE