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A consumer's guide to particle-detectors

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A Consumer's Guide to Particle-Detectors

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Notes prepared for the SRC Summer School for theoretical physicists;
Southampton, September 1976.

A CONSUMER'S GUIDE TO PARTICLE DETECTORS

INTRODUCTION

What is a Consumer?

For any type of detector there are three kinds of people in the world; the majority, who have never heard of it; the consumers, who care more about the results than about the technique; and the user who knows all of its subtleties, vices and strengths. To become a user of any technique requires months and years of experience. No lectures or notes can make a user. But all theorists, and most experimenters, have to understand and to appraise the results obtained by many techniques. They must also try to pick out the technique which should be used in the next experiment on a particular topic.

This guide attempts to give the consumer a brief comparison of major current techniques. For the theorist, or the experimenter away from his speciality, it explains some of the vocabulary and the basic parameters which tend to be assumed in a seminar or a conference talk. At the very lowest level, it may also provide material for all-purpose seminar questions of the type:-

> "Couldn't this experiment have been done better with (drift-chambers/a rapid cycling bubble chamber/string and sealing-wax)*?"

or

> "Yes, but have you allowed for the dead-time of your photo-diodes?"

Organisation of Guide

There are two sections to the guide. In Part I general problems are dealt with, such as position-detection, neutrino detection etc. Part II is a brief glossary of detector types and their basic principles of operation.

*delete as appropriate.

Basic Sources

For many of the techniques used at the CERN SPS, a useful survey is that made by the ECFA working groups in CERN/ECFA/72/4 Volume I 1972. More up-to-date studies with a bias towards e^+e^- physics are contained in the two PEP summer-studies, 1974 and 1975 (published by the Lawrence Berkeley Lab. and SLAC) and in the proceedings of the Frascati meeting c the PETRA experiments (published by DESY, Hamburg 1976).

For any specific technique, a quick scan through the index of Nuclear Instruments and Methods (N.I.M.) will usually locate a "user-level" account of the device in action. Some such specific references are included in the technique-by-technique glossary of Part II. A brief general review of detectors, including lower energy techniques, has been published by J.B.A. England (J. Phys. E (Scientific Instruments) 9, 2 (1976)). The International Conferences on Particle Physics Instrumentation have produced useful proceedings; the latest from Frascati in 197

N.B.

In all techniques mentioned, except bubble chambers, the author of these notes counts as a consumer himself. He asks the pardon of users whose specialities he may have misrepresented.

PART I - WHICH DETECTOR FOR WHICH JOB?

I.A. Continuous-Track Detectors

These usually provide a target, precision-measurement and some particle-identification, all in the same device. The bubble chamber is the most important, but cloud-chambers, streamer-chambers and emulsion fall into the same category. See Table A for a comparison of a number of important types. They all offer 4π steradians acceptance for charged tracks.

Cloud chambers are now little-used because of the long dead-time between expansions in an expansion chamber, or the shallow sensitive region in a diffusion chamber, than-in also too thin, even for hadrons, if the chamber is to be used as a target as well as a detector.

Emulsion (see Part II) is the only detector whose resolution goes down to fractions of a micron. For this reason it has been used for many years. in the study of hyperfragments. It has become more important again recently in searching for charmed particles, whose lifetimes may be too short for bubble chambers to resolve. Because stacks are relatively light and compact, they can also be flown in balloons or on aircraft to study cosmic radiation. Although a stack is continuously sensitive, from pouring to development, events are well resolved and quite large statistics (~ 10^6 tracks/sq.cm) can be accumulated. The target can never be pure H_2 or D_2. Momentum resolution is poor on all but stopping tracks. Scanning, using a powerful microscope, is relatively slow. Lambda hyperon and K^o decays are hard to find, and gamma-ray detection is poor.

The streamer chamber (see Part II) offers the 4π detection and good resolution of a bubble chamber, but it can be triggered. Unfortunately, in all but specialised experiments, it needs an external liquid target which cannot be made sensitive; that is, tracks cannot be followed right back to the interaction point, as they can in a bubble chamber or in emulsion.

I.B. Position Detectors

Table B lists six of the major types of position detector. They are all essentially detecting <u>areas</u>, mostly planar though sometimes cylindrical. In most cases information must be extracted separately to get an x and a y dimension within the detecting surface. This is often done with two orthogonal detectors close together, or with orthogonal readouts on one detector. If more than one track is expected per trigger, then three readouts are needed to resolve ambiguities, ideally at 60° to one another. (Only two stereo views are needed on an optical spark-chamber.)

These detectors are often used in groups, with drift-spaces or magnets in between, to measure angles and momenta.

TABLE A - CONTINUOUS TRACK DETECTORS

	Hydrogen or Deuterium Bubble Chamber (H_2BC)	Heavy Liquid Bubble Chamber (HLBC)	H_2 or D_2 + Neon Mixture Outside (TST - track sensitive target)	Rapid Cycling H_2 or D_2 Bubble Chamber (RCBC or RCVD = Rapid cycling vertex detector)	Streamer Chamber
Rate	∿ 2 expansions per pulse	∿ 2 expansions per pulse	∿ 2 expansions per pulse	$\lesssim$ 20 expansions/ pulse	$\lesssim$ 5 MHz beam $\lesssim$ 1 KHz, stage I trigger. $\lesssim$ 20 Hz pictures.
Target	H_2 or D_2, sensitive	C, Ne, F etc. $\lesssim$ 20% H.sensitive	H_2 or D_2 sensitive	H_2 or D_2 sensitive	External target. Not sensitive
$\Delta p/p$	≈ ½% at 1 GeV/c	≈ 5% at 1 GeV/c (from curvature)	≈ ½% in target at 1 GeV/c	≈ ½% at 1 GeV/c	≈ ½% at 1 GeV/c
$\Delta\theta$	∿ 10^{-2} radians	∿ 2 x 10^{-2} radians at 1 GeV/c	∿ 10^{-2} radians	∿ 10^{-2} radians	∿ 10^{-2} radians
Point Precision	150 - 300 μ	150 - 500 μ	150 - 300 μ	70 - 200 μ	∿ 150 μ in x-y ∿ 500 μ in z (along streamer)
Analysis	Scan + Automatic Measuring	Careful scan + Manual or Semi Automatic measuring		Scan + automatic measuring. May achieve automatic scanning, or on-line TV scan.	
Complexity & Cost	Large laboratory facilities. User plays little part in setting up. Cost ∿ 100 MSF, plus film and power.		+ ∿ 5 MSF for TST and Ne	Medium sized facilities. Users may change layout and external detectors. Costs $\gtrsim$ 5MSF	
γ-detection	$\lesssim$ 15% per γ	∿ (50-90)% per γ	∿ (50 to 90)% per γ	Poor unless external	Poor, unless external
Particle Identification	Ionisation → bubble-density below ∿ 1.2 GeV/c. Constrained fits	Ionisation and track shape below ∿ 1.5 GeV/c. Curling up of electrons + bremsstrahlung. Relativistic rise(?)	Virtues of HBC and HLBC combined.	Ionisation below 1.2 GeV/c. May use time of flight, cerenkov or relativistic rise externally.	Streamer density below ∿ 1.2 GeV/c Time of flight or cerenkov externally Relativistic rise in chamber(?).

(continued overleaf)

TABLE A CONTD.

	Hydrogen or Deuterium Bubble Chamber (H_2BC)	Heavy Liquid Bubble Chamber (HLBC)	H_2 or D_2 + Neon Mixture Outside (TST - track sensitive target)	Rapid Cycling H_2 or D_2 Bubble Chamber (RCBC or RCVD = Rapid cycling vertex detector)	Streamer Chamber
Advantages	H_2 or D_2 target. Good precision on charged tracks. Can see prongs $\gtrsim$ 1mm in length.	Dense target (for ν and nuclear interactions). Good electron and γ-ray detection; also some neutrons.	H_2 or D_2 target with γ and e detection Good precision on charged tracks. Some neutrons detected.	Can trigger flash $\rightarrow \sim 90\%$ rejection. External detectors adapted to each experiment. Higher precision on energetic tracks externally.	Flexible fast trigger. High beam rate.
Snags	Low rate. Don't see neutrals. No trigger. Precision drops at high energy.	Poor precision. Nuclear background to H_2 or D_2 events. Slow scanning. No trigger. Best for low statistics channels	Slow scanning. No trigger. Lower event rate than H_2BC because of complexity in Ne.	External detectors only cover $\lesssim 3\pi$ ster. Good trigger rejection hard to achieve.	Target outside chamber. Flares on steep tracks.

TABLE B - POSITION DETECTORS

	Scintillator Hodoscope	Drift Chamber	Multiwire Proportional Chamber MWPC	Wire Spark-Chamber	Optical Spark Chamber	Proportional Tubes; Flash Tubes
Precision	$\gtrsim$ 2 mm; usually $\gtrsim$ 10 mm	$\gtrsim$ 0.1 mm	$\gtrsim$ 30 mm (better at high pressure)	$\gtrsim$ 0.3 mm	$\gtrsim$ 0.1 mm	$\gtrsim$ 5 mm
Size	up to $\sim$ 2 m	up to $\sim$ 5 m square	up to $\sim$ 2 m square	up to $\sim$ 4 m square	up to $\sim$ 4 m square	$\lesssim$ 10 m long
Thickness	$\gtrsim \frac{1}{2}$ grm/cm^2	$\gtrsim 10^{-3}$ gr/cm^2	$\gtrsim 10^{-2}$ gr/cm^2 (lumpy)	$\gtrsim 5 \times 10^{-2}$ gr/cm^2	$\gtrsim 5 \times 10^{-2}$ gr/cm^2	$\gtrsim$ 1 gr/cm^2
Shape	Strips	Flat or cylindrical	Flat or cylindrical	Flat or cylindrical	Flat or cylindrical Narrow or wide gap.	Straight
Rate	up to $\sim$ 50 MHz	up to $\sim$ 1MHz	up to $\sim$ 10 MHz	up to 5 KHz	up to $\sim$ 1 KHz (TV readout) $\lesssim$ 20 Hz (film readout)	up to 10 MHz (proportional) $\sim$ 1 KHz (flash)
Speed of Analysis	$\gtrsim$ 10 n sec	$\gtrsim$ 1 μ sec	$\gtrsim$ 50 n sec	$\gtrsim$ 100 μ sec	$\gtrsim$ 1 m sec (TV); $\gtrsim$ 0.1 sec (film, automeasured) may need scanning.	$\gtrsim$ 100 n sec
Triggering	Own trigger	needs trigger	own trigger	needs trigger	needs trigger	Proportional may be own trigger. Flash needs trigger.
Magnetic Fields	Photomultiplier very sensitive	Can work, if E field corrected.	Don't mind	Don't mind (depends on readout)	Don't mind (except TV tubes)	Don't mind
Special Properties	Time of flight resolution to fraction of a nano-second. Liquid useful for awkward shapes. Pulse height may give dE/dx. Cheap plastics for large areas.	High precision. Low γ-conversion or interaction. Cheaper than MWPC. May be very big (with reduced precision).	Good precision and time resolution, with self-triggering. Works in a magnet. Cathode readout (inductive) can resolve ambiguities (may also reduce cost).	Cheaper than MWPC ($\sim$ 3000SF/plane, magnetostrictive) ($\sim$ 20 SF/channel, cores or capacitative).	Precision Cheaper than MWPC	Cheap. Big Thick walls or plates give γ-conversion

(continued overleaf)

TABLE B - CONTD.

	Scintillator Hodoscope	Drift Chamber	Multiwire Proportional Chamber (MWPC)	Wire Spark-Chamber	Optical Spark Chamber	Proportional Tubes; Flash tubes
Snags	Attenuation in long strips. Expensive for fine resolution (∿ 500 SF/photo-tube).	May be ambiguity of position. Cylindrical chambers need thicker cathode material. Gas may be toxic or explosive.	Expensive (∿ 100SF per wire). Mechanical and electrostatic problems limit size of chambers. Gas may be toxic or explosive.	Poor rate Generate electronic noise.	Poor rate Geometry for stereo viewing. Robbing of current in multi-track events. Electronic noise	Poor resolution

I.C. Gamma-Ray Detectors; Electron Detection

Table C compares the major devices. None of them offers the precision on gamma-ray conversion points which can be obtained in a heavy liquid bubble chamber or in a TST chamber (see Table A), though the energy resolution on gamma-rays in heavy liquids is only ~(10 to 25)%. It is possible to improve the spatial resolution of NaI or Pb glass detectors by putting thin layers of lead with spark- or wire- chambers in front of the "wall of bricks", but this leads to poorer energy resolutions (N.I.M. 120, 237 (1974)). See the 1974 PEP Summer Study (SLAC-LBL) and the notes from the Frascati discussion meeting on PETRA (DESY, Hamburg 1976) for fuller discussions of gamma-detection techniques.

These gamma detectors work by containing a complete pair-production and bremsstrahlung shower, giving a signal proportional to the total track-length in the shower. They must therefore be many radiation lengths thick, and modules are usually a few radiation lengths wide. Since they contain a lot of high-z material they tend to be extremely heavy, and may need substantial supporting structures.

Electron energies can be measured in a very similar way to γ-ray energies, since either primary particle can start a shower. Because of end effects, the calibration may be slightly different for electrons and for γ-rays.

Shower detectors can also be used to discriminate between electrons and charged hadrons. The particle momentum is first determined in a magnetic spectrometer and the energy is then measured again with a shower detector. Electrons should give the same energy in both measurements, within errors. Only about 1 in 100 hadrons will convert enough energy into an electromagnetic shower, via π^0s, to "fake" an electron.

I.D. Particle Identification

Table D lists the major techniques. They cover different energy ranges in the following way for $\pi/k/p$ separation:-

Stopping particles

Momentum from curvature + range in absorber

$\frac{dE}{dx}$ and $\int \frac{dE}{dx}\,dx$ in scintillators.

For K^+ or μ decay, can use delayed pulse in scintillator or cerenkov.

Low momenta, up to ~1.2 Gev/c

$\frac{dE}{dx}$ and momentum from curvature

time of flight and momentum from curvature. (See Part II).

~1 to ~4 Gev/c

time of flight and momentum from curvature

threshold cerenkovs (see Part II) and momentum from curvature.

~4 to ~50 Gev/c

threshold cerenkovs)
disc cerenkov (see Part II)) and momentum from curvature
relativistic rise (see Part II))

~50 to ~300 Gev/c

disc cerenkov and momentum from curvature

300 Gev/c upwards

transition radiation (see Part II) and momentum from curvature.

TABLE C - GAMMA-RAY DETECTORS

	Lead Glass Cerenkov	Sodium Iodide Scintillator	Lead-Scintillator Sandwich	Lead + Liquid Argon	Stacked Proportional Tubes
$\Delta E/_E$ FWHM	$\sim 10\% / \sqrt{E}$, E in GeV	$\sim 2\% (E)^{\frac{1}{4}}$	$\sim 20\% / \sqrt{E}$ (depending on thickness of Pb).	$\sim 2\% / \sqrt{E}$ (pure Argon) to $\sim 10\% / \sqrt{E}$ (depending on Pb thickness).	$\gtrsim 20\% / \sqrt{E}$ depending on wall thickness.
Cost	$\sim$ 2000SF for $10cm^2 x 10X_o$ brick and photomult.	$\sim$ 6000SF for $10cm^2 x 10X_o$ brick and photomult	$\sim \frac{1}{2}$ cost of Pb glass for same area and thickness, depending on construction of modules.	$\sim \frac{1}{2}$ Pb glass for same area and thickness	1 cm tubes - comparable to Pb glass for same area and thickness. 5 cm tubes are much cheaper
Energy Range	> 20 MeV	> 10 MeV	$\gtrsim$ 150 MeV	$\gtrsim$ 50 MeV	$\gtrsim$ 150 MeV
Advantages	Fast ($\sim$ 20 ns resolution). Good accuracy at high energies.	Quite fast ($\sim$ 200 ns resolution). Very accurate.	Fast ($\sim$ 20 ns resolution). Can trade-off cost for precision in energy (thickness of Pb) and spatial precision (may add layer of prop. tubes).	Cheaper for large volume detectors. O.K. in a magnet.	Cheap or good spatial resolution. O.K. in a magnet.
Snags	Spatial resolution $\sim$ brick size	Hygroscopic; needs protection. Spatial resolution $\sim$ brick size.	Spatial resolution $\sim$ scintillator width - often $\sim$ 5 cm. Need crossed-hodoscopes even to use this.	Spatial resolution $\sim$ 5 cm. Slow ($\sim$ 1 μs resolution). Cryogenic container needed.	Poor energy resolution. Clumsy shape.
	Time stability of photomultipliers must be monitored. Don't like magnetic fields.				

The momentum-limits quoted here are very rough, and are certainly wrong for some individual experiments where care has been taken to extend the range available to a particular technique.

For electron-hadron separation, threshold cerenkov counters, using an appropriate gas at atmospheric pressure, can be used over a very wide momentum range, and transition-radiation becomes useful at a few Gev/c. Shower detectors can also be used (see section I.C. above).

For a recent review, see Cashmore in the Frascati PETRA meeting proceedings.

TABLE D - PARTICLE IDENTIFICATION DEVICES (π/k/p separation)

	Time of Flight (between scintillators)	Threshold Cerenkov	Disc Cerenkov	Relativistic Rise (e.g. ISIS)	Transition Radiation (Foils or foam + MWPC)
Energy Range	≲ 2 Gev/c	≲1 Gev/c Solids & liquids ≲4 Gev/c Aerogel from ~2 Gev/c to ~70 Gev/c in Gases.	From ≲4 Gev/c to ~300 Gev/c	From ~5 Gev/c to ~ 70 Gev/c	> 300 Gev/c
Rate	up to ~ 10 MHz	up to ~ 10 MHz	up to ~10 MHz	≲ 20 KHz	up to ~5 MHz
Acceptance	Can be large, both in angle and momentum	Each module has quite small coverage in momentum. Angular acceptance can be quite good.	Very small in both angle and momentum	Large in both angle and momentum.	Can have good angular acceptance.
Advantages	Cheap and flexible. at low energies. Fast.	Fast. Better angular acceptance than disc.	Fast. Good in beam or spectrometer arm.	Large acceptances. Matched to downstream side of bubble-chambers.	All there is, in its range. Cheap and good coverage. Quite fast.
Snags	Only up to ~2 Gev/c.	Need elaborate [illegible] of modules to [illegible] and angle coverage.	Small acceptance. Delicate optics and very long at high energies.	Slow. Bulky. Doesn't like high magnetic fields.	We haven't got to 300 Gev for secondaries yet! New technique: variable [illegible].

Photomultipliers don't like to be in magnetic fields.

These are all velocity-measurement techniques. A particle's momentum must also be known before the mass can be identified.

I.E. Hadron Calorimeters

These operate by measuring the total energy deposited by a hadronic shower, in a similar way to shower detectors for γ-rays and electrons. They are used most frequently for neutrons or K^0_L, which can only be detected by making them interact. Because strong-interaction collision-lengths are proportional to A, not to Z^2, hadron calorimeters have to be even thicker than γ-ray detectors. They also tend to convert a smaller fraction of the incoming energy into a measurable signal - soft neutrons may be lost and nuclear stars may deposit energy in the insensitive parts of the equipment such as converter plates.

The calorimeter can have many layers of iron plates, interspersed with liquid scintillator, plastic scintillator, liquid argon (see Part II), or some other sampling material. Such composite calorimeters have $\frac{\Delta E}{E} \sim \frac{50\%}{\sqrt{E}}$ (E in Gev). More refined versions have no converter plates, just many metres of the sensitive medium, and may achieve $\frac{\Delta E}{E} \sim \frac{25\%}{\sqrt{E}}$.

Thick-plate spark chambers are also sometimes used. They have poor $\frac{\Delta E}{E}$, using the sum of the sparks seen to measure energy. But they may achieve a better resolution on the interaction point of the incoming neutral than is possible in a scintillation- or argon-calorimeter.

A good review is given by Büsser in the Frascati Petra meeting proceedings. See Barish et al, Nuclear Instruments and Methods 116, 413 (1973), for a concise account of the properties of the hadron calorimeter which they used as a neutrino detector. Also see NIM 112, 313 (1974) for a relatively compact hadron calorimeter, used at Serpukhov, which also served as an effective γ-ray detector.

Hadron calorimeters tend to be both more bulky and more massive even than γ-ray detectors.

I.F Muon Identification

For high-energy muons the important property is penetration through dense matter. They do not make large angle scatterings due to the strong interaction, and they are not absorbed. The range of a 600 Mev/c muon in lead is about 37 cms, i.e. about two nuclear absorption-lengths for hadrons. Above 1 Gev/c it is very improbable that a hadron will penetrate a wall of steel, lead or concrete many absorption-lengths thick, but muons will pass through with only $\frac{dE}{dx}$ losses and multiple scattering. A crude muon detector merely detects the charged particle in a position detector before the wall and detects it again coming out of the back. There can be hadron "punchthrough" in such a set-up, since the hadron shower will penetrate quite a few absorption-lengths beyond the initial interaction point. More sophisticated muon detectors have a sandwich structure in which a single continuous track is required to pass through a number of layers of absorber, each a few collision-lengths thick, with position-detectors in between the layers.

Steel is the most popular absorber, having the best combination of price, density and multiple-scattering. It may also be magnetised by relatively small currents, giving a curvature to the muon track which can be used for momentum measurement.

The type of position detector used varies according to the area to be covered and the money available. Downstream of a bubble chamber, the E.M.I. (External Muon Identifier) for neutrino experiments needs to be a few metres in area, but it should have good spatial resolution. Multi-wire proportional chambers (see Part II) have been used for this purpose, with the chamber coil and added metal as an absorber (see CERN Courier 16, 136 (April 1976)). At DORIS the solenoid detector PLUTO has been surrounded on all sides by absorber, giving a very large muon-detection area. This is covered with proportional tubes (see Part II) which give reasonable position resolution at relatively low cost. Drift-chambers and scintillation hodoscopes are also extensively used in muon detectors.

Very low energy muons can be detected by a quite different technique. They are allowed to stop in a piece of material or in a scintillator and a delayed pulse is detected from the subsequent decay to an electron plus neutrinos.

I.G High Energy Neutrino Detectors

The first requirement is mass but, since the cross section is proportional to energy, at the SPS the interaction rate becomes reasonable even in a few hundred kg of material. Nevertheless, most neutrino detectors present some tonnes of target to the beam. After a thick steel or earth shield, the beam at CERN or at FNAL is concentrated in a cone of about 1m diameter, but with a considerable tail at larger distances. It is accompanied by a shower of muons, γ-rays and neutrons produced by the interaction of the neutrinos themselves in the back of the muon shield.

A detector must consist of i) a veto layer, to eliminate non-neutrino interactions; ii) a target, and iii) a detector for secondary particles. The "first-generation" neutrino experiments used relatively simple set-ups. The heavy-liquid bubble chamber Gargamelle is long enough that it can combine all of these functions within one device. Incoming charged particles can be seen clearly. Incoming neutrons or γ-rays can be eliminated by looking at the distribution of events as a function of the number of radiation lengths or nuclear absorption-lengths from the front of the chamber. The target in Gargamelle is normally a heavy nucleus, though with propane it is possible to isolate some hydrogen events. The heavy liquid detects most of the secondary particles and identifies many of them. Charged hadrons usually interact before leaving. Low energy charged particles may stop with characteristic track-shapes. Muons pass undeviated through a number of collision-lengths before leaving. Electrons and gamma-rays produce showers which can be recognised and measured. Neutrons and K^0_L may

also be recognised by their interactions. In fact, the chamber is dense enough that the incoming neutrino energy can be very roughly estimated just by adding together the energies of all the detected particles.

Electronic experiments have generally used more massive detectors than Gargamelle; looking something like a hadron calorimeter followed by a muon identifier (see sections I.E and I.F above). They have the disadvantage that the close details of the neutrino interaction are not visible, since the interaction is inside a steel plate or a large bath of scintillator. Their advantage is high statistics and in very clean muon detection.

The next round of experiments will improve on the previous techniques in a number of ways. Large hydrogen and deuterium bubble chambers are being used, with external muon identifiers. There are also plans to use large-volume (2 m^3) track-sensitive-targets (see Table A) inside hydrogen-neon chambers to combine the particle-detection of heavy liquid with a clean target. More elaborate electronic experiments involve large volumes of liquid scintillator or of argon split into small cells to give reasonable position resolution. Passive liquid-hydrogen targets are also planned.

Emulsion stacks, followed by muon-detectors are being used to search for very short-lived states which might be produced by neutrinos. An interesting event is recognised by observing the muon in an external electronic system, and a spark chamber is used to identify the accompanying hadron tracks. These are followed back into the emulsion where the interaction can be studied with a spatial resolution of $\sim 1\ \mu$.

PART II - CONSUMER'S GLOSSARY OF DETECTION TECHNIQUES

Aerogel

A very low-density solid material which can be used as a radiator in threshold cerenkov counters (Q.V.), bridging the gap in refractive index between high pressure gases and normal solids. It is formed in blocks or in granules but it cannot be used in large thicknesses because it diffuses light. Refractive indices available are around 1.025 to 1.06.

ref. e.g. Nuclear Instr. & Meth. 118, 177 (1974)

Automatic Measurement of bubble chamber pictures.

Events are scanned by an operator who records guide-points on tracks and other interesting features, using a low precision device. A computer-controlled machine then automatically finds the frame, locates the event and digitises all features of interest, to an accuracy of about 4 μ on film. Common types are:-

HPD or FSD, which sweeps a spot across the film mechanically in a fixed raster. A large on-line computer is needed.

PEPR, POLLY and ERASME which use a cathode ray tube to give a programmable spot. Needs a large on-line computer.

SWEEPNIK which uses digitally controlled mirrors to follow tracks with a rotating line segment. Needs only a "mini" computer on-line.

ref. e.g. Proceedings of HPD Collaboration Meeting 1974
Rutherford Report RL-75-023.

Bubble density

The number of bubbles per centimetre on a bubble-chamber track is directly related to the rate of energy loss $\frac{dE}{dx}$ of the particle and hence to the velocity β. If the momentum of the particle is known, then it may be possible to differentiate between particles of differing mass, especially π, K and p, by measuring the bubble density. Automatic measuring machines (Q.V.) give very precise bubble-density measurement on clear tracks. The π/K/p separation works well up to about 1.2 Gev/c in hydrogen and deuterium. It may also be possible in the 5 to 30 Gev/c range in hydrogen-neon mixtures, using the relativistic rise (Q.V.) in dE/dx.

ref. (Fisher et al, Nucl. Instr. Meth. 133, 29 (1976).

Dead-time

The time after a signal during which a detector cannot detect another signal. For a photomultiplier with plastic scintillator the dead-time may be ≲ 100 ns. For a spark-chamber it can be up to a millisecond before the ions left from a spark have cleared away and the H.V. is ready to pulse.

Disc Cerenkov or focusing cerenkov (see Table D).

This is a high-precision device for use in beams or in spectrometer arms, where the particles to be identified have a very restricted range of angles and momenta.

The cone of cerenkov photons makes an angle to the particle which depends only on velocity and the refractive index of the medium. For a "wanted" particle the light is focused to a ring on an anular mask with photomultipliers (Q.V.) behind it. Unwanted particles give the wrong size of ring and are not detected. At very high energies $\beta \to 1$

for all particles, so low pressure gases have to be used with refractive index $n < 1/\beta$. Very few photons are then produced per unit length, and the counter must be some tens of metres long to give a clear signal.

refs. ECFA working groups on SPS CERN/ECFA/72/4 Vol I
Nucl. Instr. and Meth. 111, 397 (1973)
Meunier, 1973 Instrumentation Conference, Frascati.

N.B. Strictly, there are two types of focusing cerenkov counter;
a) DISC ≡ "Differential isochronous cerenkov", with optics corrected for chromatic dispersion.
b) DIFC ≡ "Differential focusing cerenkov" uses uncorrected optics and is less efficient.

Drift Chamber

Very flexible and important position detectors (see Table B). A charged particle liberates ions in a thin layer of gas (~ 1 to 4 cm thick). The electrons drift in a bunch over a few centimetres in a field of about 1 KV/cm. Their velocity (about 200 ns per cm) is stabilised against small variations in voltage or temperature because the gas contains polyatomic molecules such as isobutane which can absorb a lot of energy at each electron-molecule collision. When the bunch of electrons arrives at the very fine sense-wire it is amplified by gas-multiplication (Q.V.) and a pulse is transmitted through the wire. The time-delay of this pulse, after the original passage of the particle as measured by a scintillation counter (say), is due to the drift time of the electron bunch. Precise measurement of the time delay can give a resolution down to ~100 μm.

Special techniques have been evolved to operate the chambers in magnetic fields which deflect the direction of drift.

refs. Frascati PETRA meeting proceedings; talks by Walenta and Turlay; also
Nuc. Instr. & Meth, 124, 189, 1975, and reference back from that.
Proc. of 1973 Instrumentation Conference, Frascati.

Emulsion (see Part I.A)

Photographic emulsion, consisting of silver halides in gelatin. This may be poured in pellicles a few millimetres thick and stacked to give a dense detector with very high resolution. It may also be coated onto plastic or other materials which are stacked to form an "emulsion chamber". It is scanned under a microscope at high magnification.

ref. Barkas "Nuclear Research Emulsions", Academic Press (1973)

Flash tube (see Table B)

A glass tube filled with gas. Arrays of these tubes are placed between electrodes which are triggered and pulsed at high voltage. This causes breakdown in those tubes which contain ionisation from the passage of charged particles. The breakdown of the gas fills the tube with a luminous plasma. A large inductive signal on a metal probe placed near the end of each tube may be used for readout (Q.V.), or the ends of the tubes may be photographed.

ref. e.g. Nuclear Instr. & Meth. 125, 189 (1975)
and " " " 124, 101 (1975)
also 1973 Instrumentation Conference, Frascati.

Gas Multiplication

The process of amplification used in drift chambers (Q.V.) and multiwire proportional chambers (Q.V.). The electron cloud from an ionising particle drifts towards a very fine wire (20 μ diameter, gold-plated tungsten for example). It sees a very high electric field within ~ 50 μ of the wire and the electrons are accelerated sufficiently to ionise the gas around the wire. This releases more electrons and a cascade builds up. The resultant pulse on the wire may be amplified to ~ 10^6 times the charge in the original electron cloud due to secondary electrons from the cascade. A special gas must

be used, with molecules in it (such as isobutane) which are opaque to ultra-violet light. Otherwise the plasma spreads and spark breakdown occurs.

This amplification is used to match a signal from only a few electrons into reliable and economical fast electronics.

Hodoscope

A stack of counters side by side. E.g. a "fence" of scintillators.

Isis (see Table D)

A particle identifier using the relativistic rise (Q.V.). A kind of drift chamber (Q.V.) with many sense-wires inside a volume ~2m x 2m x 4m. It makes many samplings (∿ 100) of the ionisation deposited by fast charged particles in an Argon-based gas mixture. If the momentum of a particle is known, from a bubble chamber or other device, then it can be identified as π, K or p, over the range from ~ 5 to ~70 Gev/c.

ref. Nuclear Instr. & Meth. 119, 499 (1974)
also (similar device) 123, 237 (1975)

Lead Glass (see Table C)

Optical glass containing lead; cast in blocks; optical attenuation length $\geq \frac{1}{2}$ m and radiation-length 2.5 cms. Electrons in an electromagnetic shower emit cerenkov radiation which is picked up by a photomultiplier (Q.V.). Blocks of ~ 10 cm x 10 cm x 50 cm will contain a high-energy shower (though shower penetration is energy-dependent).

ref. e.g. Nuclear Instr. & Meth. 120, 237 (1974)
and 1973 Instrumentation Conference, Frascati.

Liquid Argon (see Table C)

Being used increasingly for γ detection, in hadron calorimeters and for high resolution position detectors. Does not give gas multiplication, just collects ionisation so must use high gain electronics. This is not such a problem for the multiplate charge-collectors in a large calorimeter. Its great advantage over liquid-scintillator is that the output is proportional to the energy deposited, irrespective of the ionisation density on the tracks (scintillators saturate on heavily-ionising tracks).

ref. Nuclear Instr. & Meth. 120, 221 (1974)
" " " 122, 319 (1974)

Multiwire Proportional Chamber (m.w.p.c.)

Very important and varied family of position detectors (see Table B). Contain a large number of fine sense-wires in a plane, with spacing ~ 1 mm to ~5 mm. These form the anode of a gas cell about 1 cm thick. The two cathodes may be simple conducting foils, or may have a signal-collecting pattern etched onto them. A charged particle produces a bunch of electrons which migrates to the nearest one or two sense-wires where gas-multiplication takes place (Q.V.). The commonest form of readout is to amplify the pulse on each sense-wire. This is expensive because of the large number of wires, each with a separate electronics-channel. Recent developments use inductive readout in one or both of the cathode planes (see e.g. Nucl. Instr. and Meth. 131, 229 (1975)), and may include a delay-line system which acts as a position-to-time converter and needs only one channel of electronics per cathode (see e.g. Nuclear Inst. and Meth. 120, 17 (1974)). For a large detection system based entirely on m.w.p.c. see Nucl. Instr. and Meth. 125, 19 (1975) and 115, 235 (1974) (the CERN ISR Split-Field-Magnet System).

Proportional Tube (see Table B)

Conducting tube with a fine sense-wire stretched down the centre at ~ + 1 kv. Any ionisation in the tube gives a bunch of electrons which is amplified by gas-multiplication (Q.V.). Can be used in hodoscopes and especially, with thick metal walls, as γ-ray detectors.

ref. Nucl. Instr. & Meth. 115, 461 (1974)
1973 Instrumentation Conference, Frascati.

Photomultipliers

Vacuum tubes consisting of two essential parts:-

1) A photocathode; half coated with an alkali-metal film. Photo-electrons are accelerated from this to a chain of

2) Dynodes. These electrodes, each at ~200 v potential to its neighbour, emit secondary electrons when struck by electrons from the previous stage. The few tens or hundred of photo-electrons from the photocathode may be amplified by up to x 10^5 to x 10^8 in passing down a chain of ~6 to 14 dynodes.

The output pulse has a sharp rise which can allow coincidence timing to a fraction of a nanosecond.

ref. Manufacturers catalogues (EMI, RCA etc.)
also Pietri in 1973 Instrumentation Conference, Frascati.

Relativistic-Rise of dE/dx as $\beta \to 1$.

This effect, long predicted but only recently used, is limited by the "density effect" - a long-range response of the electron plasma in condensed material. In noble gases dE/dx rises from minimum by about

50% at S.T.P., so it can be used to measure the velocity of fast particles in such devices as ISIS (Q.V.). In liquid neon there is about a 30% rise but in liquid hydrogen the rise is negligible (see "Bubble density" above).

Rapid Cycling Bubble Chamber ("RCBC" or "RC Vertex Detector") (see Table A).

A small bubble chamber which can be driven at 10 to 50 Hz. The optics and expansion system are normally designed to give good all-round access for external electronic detection devices.

ref. CERN/ECFA/72/4, Vol.I, p.119.
or C.M. Fisher in Proceedings of 1973 Instrumentation Conference, Frascati.

Scintillators (see Table B)

Materials which convert the energy deposited by a charged particle into photons. Many different types. The most popular for high-energy physics are certain plastics, liquids and sodium iodide (Q.V.). A photomultiplier (Q.V.) with a gain of up to 10^7 is used to generate an electronic pulse, proportional to the number of photons collected. The scintillator is often connected to the photomultiplier by a "light pipe" of transparent plastic.

ref. see manufacturers catalogues - e.g. Nuclear Enterprises.
also Zichichi, in Proceedings of 1973 Instrumentation Conference, Frascati.

Solid-state Detector

Of limited application at high energies. Chips of semiconductor may be constructed to act as small hodoscopes, as dE/dx counters or as total

absorption counters for slow particles. They are usually only a few centimetres across and give rather slow pulses, compared with scintillators.

ref. e.g. N.I.M. 111, 567 (1973)
England, J.Phys.E (Sci.Instr.) 9, 2 (1976)

Spark Chambers (see Table B)

Once the major position detectors, now being superseded by multiwire-proportional and drift-chambers. Basically a gas-filled parallel-plate condenser which can be pulsed at ~10 kv. Ionisation causes a spark-breakdown between the plates, which will follow a track quite closely. Enormous range of readout techniques, for example:-

Sonic - detects sound waves from spark at four microphones on edges of chamber.

Optical - uses a transparent edge, or wire electrodes, to photograph the spark in stereo views.

Cores - Wire-plane electrodes have ferrite-cores threaded around the lead-in wires. These are flipped in magnetisation by the spark current, and later interrogated by computer-type circuitry.

Magnetostrictive - A metal "wand" is placed close to the lead-in wires. When a spark pulse passes a mechanical pulse is generated in the wand. Its delay in reaching a transducer at the end of the wand gives the position of the wire which fired.

Capacitative - a number of wires may be ganged together to form a hodoscope. The spark pulse induces a charge on a capacitor which can be interrogated by computer-type electronics.

Wide-Gap - a form of optical chamber in which the plates are ~ 4 to 10 cm apart. The spark follows a track very faithfully and a precision of ~ 100 μ can be achieved.

ref. Proceedings of 1973 Instrumentation Conference, Frascati.
Shutt "Bubble and Spark Chambers". Academic Press.

Streamer Chamber (see Table A)

A very wide-gap spark-chamber without sparks. Uses short (~20 ns), very high voltage (> 15 kv/cm) pulses, to produce short (~ 1 cm) plasma streamers on the ionisation left by a charged particle. These can be photographed on 5000 ASA film.

refs. Talk by Ladage in Frascati, PETRA meeting proceedings 1976.
also ECFA studies on SPS, CERN/ECFA/72/4, Vol.I, p.132.

Sodium Iodide (see Table C)

Large (expensive) crystals form very efficient γ-ray detectors. The material is hygroscopic. Scintillation-light output is excellent, so there is a very small statistical fluctuation on the energy measured. The energy resolution is quite good even down to a few Mev. Radiation-length 2.6 cm.

ref. Hofstädter in 1973 Instrumentation Conference, Frascati.

Transition-Radiation (see Table D)

Analagous to cerenkov radiation, but produced when an extremely relativistic particle passes from one refracting medium to another. The intensity of X-rays produced depends on γ rather than on β. The X rays are produced in a multifoil or a foam radiator and detected in a xenon-filled multiwire-proportional-chamber (Q.V.).

ref. Nucl. Instr. & Meth. 130, 365 (1975)
or Nucl. Instr. & Meth. 123, 231 (1975)

Track-Sensitive Target (TST) (see Table A)

A transparent box filled with H_2 or D_2, inside a bubble-chamber filled with a neon-hydrogen mixture. At ~ 29 to 31°K, with appropriate mixtures, the liquids in the target and outside it can both be made

sensitive. The chamber expansion is transmitted to the liquid in the target by a slight flexing of the walls of the box, which remain flat enough to give negligible optical disturbance. The radiation-length in the external mixture is ~30 cm to ~80 cm, compared with ~10 m in liquid H_2, so γ and electron detection is much improved.

ref. e.g. CERN/ECFA/72/4, Vol.I, p.13.

Time of Flight (see Table D)

A particle-identification technique normally employed with scintillation counters (Q.V.). A particle's momentum is known, from curvature in a magnet, and its velocity is measured by timing its passage between scintillators a few metres apart. Its mass can then be determined. This technique is only useful at momenta below ~2 Gev/c where β is significantly different from 1.

Threshold Cerenkov Counter (see Table D).

A counter in which a liquid, solid, gas or aerogel (Q.V.) is selected so that one type of particle, in a given momentum-range, will be above the velocity of light in the medium, but a heavier particle of the same momentum will be below the velocity of light. Cerenkov light from the lighter particle is collected into a photomultiplier. Heavy particles may give occasional "punchthrough" by knocking-on an atomic electron (δ-ray) which will give a spurious cerenkov signal.

ref. e.g. PEP summer study 1974.
or Meunier in 1973 Instrumentation Conference, Frascati.