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THE HIGH-DENSITY PROPORTIONAL CHAMBER
AND ITS APPLICATIONS

A.P. Jeavons

CERN, Geneva, Switzerland

CERN LIBRARIES, GENEVA

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ABSTRACT

The recent development of the high-density proportional chamber -- a proportional chamber with solid converters -- has provided important, new imaging possibilities for low-energy neutral particles.

The principal device realized to date is a high spatial resolution (2 mm FWHM) positron camera. This has been used for angular correlation studies of positron annihilation radiation for condensed matter physics research, and for three-dimensional medical imaging of positron radioisotope distribution. For these applications, a new converter, made of bismuth-doped araldite, is described, which combines good detection efficiency (10%) and coincidence time resolution (100 nsec) when operated with carbon-dioxide gas.

The addition of a gadolinium foil to a high-density proportional chamber affords an efficient detector for thermal neutrons that maintains the good spatial resolution at large angles of neutron incidence. With a hafnium foil, the same properties are possible for epithermal neutrons.

Solar neutrino detection, electrophoresis, and radiochromatography are other fields of possible application.

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1. INTRODUCTION

The proportional chamber is an elegant detector of ionizing radiation. For a relatively low cost it can give a high detection efficiency and good energy, space, and time resolutions. In the field of particle physics research, the proportional chamber and the drift chamber are now established as the most widely used detectors of ionizing particles^{1,2)}.

Another wide field of activity that could benefit greatly from the properties of the proportional chamber is the detection of low-energy neutral radiation, i.e. X-, gamma-rays, and neutrons. Despite the prospects, progress has not been dramatic, largely because of the problem of converting the radiation into an ionizing form, without losing the intrinsic advantages of the proportional chamber. For 8 keV X-rays, conversion in the gas in the chamber is very successful: high efficiency, combined with millimetre spatial resolution and reasonable energy and time resolutions, is possible using argon or xenon at atmospheric pressure³⁾. Similarly, thermal neutrons may be detected with BF_3 ⁴⁾ and ^3He ⁵⁾ gases. As photon energy increases, gas conversion becomes less and less useful because the photoelectric capture cross-section falls rapidly and the range of the photoelectron increases: efficiency, and spatial and energy resolutions all degrade. Raising the gas pressure helps⁶⁾; it is even possible, although technologically difficult, to use liquid argon or xenon⁷⁾. Carrying this process to its logical limit suggests the use of solid converters. The resulting high-density proportional chamber⁸⁾ (HDPC) is now demonstrating some new detection possibilities for gamma-rays and neutrons.

2. THE HIGH-DENSITY PROPORTIONAL CHAMBER

Figure 1 illustrates the principle of the HDPC for detecting high-energy photons. In the direction of the incoming photon, the converter is thick, so that a high probability exists for converting the photon into an electron by the photoelectric effect or by Compton scattering. The converter consists of thin bars, so the electron, which scatters isotropically, can have a high probability of escaping to a hole and producing free electrons by gas ionization. These free electrons may then be ejected from the hole by an electric drift field, and detected with a

proportional chamber. If the bar size is correctly chosen, the fast electron will not propagate to a second hole and so the converter can combine a high detection efficiency with good spatial resolution. The time resolution will depend on the drift time of the free electrons in the gas in the hole. Energy resolution will be virtually non-existent owing to the random ionization loss in the bar.

Two methods have been tried⁸⁾ for obtaining a drift field in the holes. The first method uses a slightly conductive block, e.g. made from glass tubes (Fig. 2a), which is placed between two metallic grids. Channel-plate technology is particularly interesting in this respect⁹⁾. A simpler technique is to fabricate a stack of alternate conducting and insulating layers. The drift field is applied by connecting a resistor chain to the conducting sheets. This method was first demonstrated many years ago with a proportional counter^{10,11)}. The conducting layers consisted of concentric rings of lead around the anode wire of the counter, and the insulating layers were simply gaps between the rings (see Fig. 3). The detection efficiency of the four-layer structure was 2-3% for photon energies from 0.2-2.0 MeV. This method of construction extends naturally to the proportional chamber. The rings are replaced by strips "edge-on" above the wires. By folding the strips in a concertina fashion, the hole structure of Fig. 1 is created. Four-layer honeycomb converters of this nature (Fig. 4) have been reported¹²⁾: detection efficiencies are 2.5% per converter at 0.5 MeV, the same as the earlier proportional counter work.

At CERN, a different method of construction has evolved which has the advantage of many more layers, and packs more bars into a given area: a higher detection efficiency and better time and space resolutions result. The converter is made as a sandwich of alternate conducting and insulating grids (see Fig. 2b). The holes in the grids have been cut chemically, and by drilling with a numerically controlled drilling machine. Hole size may be optimized for the particular application, as may also the converter material. Detecting high-energy gamma-rays requires a material with a high atomic number, e.g. lead, whilst at lower energies (100 keV) an atomic number of about 40 is optimum. For neutron detection, lithium,

boron or gadolinium are possible materials. These questions are considered further in the following sections, and Refs. 8 and 9 should be consulted for more details, in particular for theoretical aspects.

The design of the proportional chamber itself follows standard techniques, except that two-dimensional read-out is required. Various techniques exist¹³⁻¹⁶): we follow amplifier-per-wire practice adapted to the positive pulses on the orthogonal cathode planes. The cathode pulses show a broad distribution and it is necessary to record the centre-of-cluster^{17,18}) to define the avalanche position (see Fig. 5). This read-out method has the advantages of sensitivity, due to direct coupling to the cathode wires with charge-sensitive amplifiers¹⁹), and speed (100 nsec dead-time) due to its digital nature. Further, only standard electronic digital and analogue components are used.

3. A POSITRON CAMERA

To date, work has concentrated on making a positron camera, i.e. imaging, in coincidence, the two antiparallel 0.5 MeV gamma-rays resulting from positron annihilation. The applications of this camera to condensed matter research and medical imaging are described in the next sections. Here, the camera construction and performance is detailed.

Figure 6 shows one of the two chambers forming the camera. It has two converters, one on each side of the wire planes, and an active area of 10×10 cm. The converters are offset so that the bars of the one are behind the holes of the other. Each converter is made of 75 lead-bismuth alloy grids 0.25 mm thick, interleaved with 0.1 mm thick glass-fibre epoxy-resin grids. The holes are 0.8 mm in diameter, close packed on a hexagonal pattern with a pitch of 1 mm. Proportional chamber construction follows normal techniques. Anode wires are of 20 μ m diameter gold-plated tungsten wire spaced at $\sqrt{3}$ mm (to fit behind the rows of holes), and cathode wires are 100 μ m spaced at 1 mm. Anode-to-cathode interplane distance is 3 mm. The chambers are operated with free-flow isobutane gas with 3.8 kV on the anode planes and 5 kV drift voltage on the converters. For 660 keV gamma-rays

from ^{137}Cs , the efficiency of each converter was measured to be 7.5%, i.e. 15% per chamber, and the spatial resolution to be 1.2 mm FWHM (see Fig. 7). In coincidence operation, the camera showed a time resolution of 500 nsec, which corresponds to the known drift velocity, $5 \text{ cm } \mu\text{sec}^{-1}$, of electrons in isobutane, through the full thickness of the converter.

The two parameters, detection efficiency and time resolution, are critical parameters concerning the operation of the camera at high data rates, when the occurrence of accidental coincidences becomes significant. It turns out that the figure-of-merit for a camera is $(\text{efficiency})^2/\text{time resolution}$. A new converter has now been made that greatly improves this figure-of-merit. It consists of epoxy-resin fibre-glass sheets, doped with bismuth powder, which are stacked and drilled. The improvement stems from the reduced density of 4 g cm^{-3} compared with pure lead or bismuth (10 g cm^{-3}), since the fast electrons have a higher probability of escaping from the bars into the holes. Of course, the photon conversion probability is reduced, but over-all a higher efficiency may be obtained from a thinner converter. Figure 8 shows the time resolution of an 8 mm thick converter, in coincidence with a scintillator. The converter efficiency is 10%. With isobutane gas the time resolution saturates, with the electron drift velocity, at 150 nsec. Operated with carbon-dioxide gas and a high drift field, 100 nsec is obtained, since carbon dioxide does not show a saturating drift velocity and is twice as fast as isobutane at high drift fields. The figure-of-merit for this new converter is a factor of 10 better than that for the previous converter.

4. ANGULAR CORRELATION MEASUREMENTS

When a positron penetrates condensed matter, it thermalizes or loses its momentum before annihilating with an electron. It follows that the photon pair resulting from annihilation will carry with it a knowledge of the momentum of the electron with which the positron annihilated. Thus positrons may be used as a probe for studying electron momentum distributions -- a knowledge of which is of fundamental importance for condensed matter research. A direct measurement of

such distributions may be made by mapping the angular differences of the two photon directions from 180° . Since these angles are small, typically a few milliradians, detectors with a good spatial resolution situated far from the specimen are a prerequisite. Traditionally, slit-collimated single sodium-iodide counters are placed on either side of a specimen irradiated with positrons. The slits are moved to map out the angular distributions. Replacing these counters with a camera provides two important advances: two-dimensional information, and an increased data rate due to simultaneous collection over the full angular distribution. A multi-crystal sodium-iodide camera²⁰⁾ has recently been applied successfully to this problem. The present camera gives a better angular resolution. The results of preliminary studies on copper²¹⁾ and aluminium²²⁾ crystals have been reported. Figure 9 shows a typical result for aluminium: it is a visualization of the well-known spherical Fermi surface of aluminium. The cut-off at 6.8 mrad marks the Fermi level of aluminium at 11.8 eV. Additionally, detailed structure is evident. Work has continued on a detailed study of the Fermi surface of copper, the results of which are presented in a second paper²³⁾.

5. MEDICAL POSITRON IMAGING

Imaging positron annihilation offers a very significant advantage over conventional medical radioisotope imaging. By recording, in coincidence, both of the antiparallel gamma-rays, when the detectors are relatively close to the object and the angular dispersion due to electron momenta is negligible, directional information is obtained as well as positional. Thus no gamma-ray collimator is required, and a big increase in sensitivity results. In addition, tomographic reconstruction methods may be applied to furnish three-dimensional images. Scintillation cameras, in various forms²⁴⁻²⁸⁾, are being applied to this problem. A limited spatial resolution ~ 1 cm and sensitivity to Compton-scattered radiation seem to be the principal difficulties. Proportional chambers equipped with the honeycomb converters mentioned earlier have also been used for positron imaging²⁹⁾. Spatial resolution is improved (7 mm) but the counting rate in a clinical imaging situation is low -- 80 c.p.s.³⁰⁾ -- owing to a low detection efficiency.

The present camera has been assessed for medical imaging²²⁾, for the configuration shown in Fig. 10. The distance D between the chambers was 20 cm. To avoid a large parallax error, only one converter on each chamber was used, giving a detection efficiency of 7.5%. The coincidence time window was set to 400 nsec. An angular acceptance of $\pm 25^\circ$ was allowed. Figure 11 shows the high spatial resolution obtainable with this camera: the measured width of a 1 mm diameter point source located midway between the chambers is 2.4 mm FWHM for the source in air. The count rate is limited by the occurrence of accidental coincidences: 3000 c.p.s. was obtained for an accidentals rate of 30% with a sensitivity of 25 c.p.s. per μCi . When the source was placed in a 15 cm diameter water bath the spatial resolution degraded only slightly to 2.6 mm; Compton scattering increased the background, which remained random.

The next camera will use four of the bismuth-doped araldite converters that were described in Section 3. These will give a detection efficiency of 20% per chamber and a time resolution of 100 nsec. Then the figure-of-merit, $(\text{efficiency})^2/\text{time resolution}$, will be improved by a factor of 40, and it follows that the maximum count rate for a source in air will be $\sim 10^5$ c.p.s. The effect of Compton scattering in a typical imaging situation is to limit this rate to about an order of magnitude less, i.e. $\sim 10^4$ c.p.s., which will provide a three-dimensional image in 5-10 minutes.

If an extended object is placed between the chambers, focused tomograms of the activity distribution in the object are produced. Each tomogram consists of a single plane in focus with defocused contributions from all other planes superimposed. Mathematical reconstruction is required to remove the off-plane smearing and produce a sequence of sharply focused object activity distributions. We have used a method in which the blurred background is eliminated from a series of two-dimensional planes through the object³¹⁾. Noise instability problems at low spatial frequencies are overcome by matrix inversion by singular value decomposition³²⁾. A full three-dimensional method³³⁾ has also been tried with similar results.

A mouse was injected with 5.7 μCi of ^{18}F , about half of which was taken up by the skeleton within one-half to one hour of the injection. Imaging was performed for about 2 hours at a rate of 100 c.p.s. (limited by the decaying source strength), in order to accumulate 5×10^5 coincidences. The results, before and after reconstruction, are shown in Fig. 12, and may be compared with an X-ray photograph (Fig. 13). The importance of the reconstruction in providing excellent tomographic images is obvious. Bone structure is clearly revealed, and the very intense region near the base of the spine is due to substantial uptake of ^{18}F in the kidneys. The much larger, improved camera now under construction should provide images of similar detail, in clinical applications, and should be an important imaging device for nuclear medicine.

6. THERMAL NEUTRON IMAGING

At first sight it would seem that making a drift space of neutron-sensitive material such as boron, lithium, or gadolinium will extend the properties of the HDPC to thermal neutrons. This approach, however, leads to a low efficiency because the range of the α particles from neutron capture in boron or lithium, or internal conversion electrons from gadolinium, is $\sim 10 \mu\text{m}$: these ionizing particles have little chance of escaping from the bars. A slightly different technique may be employed. The thermal neutron absorption cross-section of gadolinium is so large that a $10 \mu\text{m}$ thick foil will stop nearly all the incident neutrons whilst allowing the internal conversion electrons to escape. Combining such a foil converter with a high-density drift space to restrict the range of the emerging electrons affords an efficient detector with a good spatial resolution³⁴⁾. Figure 14 illustrates the detector. Owing to the exponential absorption in the foil, collecting the back-scattered electrons is more efficient than collecting those transmitted. Other neutron resonances may be used to obtain similar results at shorter neutron wavelengths. The choice is restricted to stable parent and product nuclides that also show the high internal conversion probability. Hafnium-177 is particularly interesting for epithermal neutrons (1-2 eV). Unfortunately, ^{149}Sm and ^{113}Cd with strong resonances in a useful wavelength region have a much higher first excited-state energy than gadolinium and do not show much internal conversion.

Tests at the Institut Laue-Langevin at Grenoble, on a chamber of 4×4 cm size, have already been reported³⁴⁾. Using natural gadolinium, a detection efficiency of 22% was recorded in the back-scattering mode. Spatial resolution, independent of the incident neutron angle, was about 1 mm, as expected. Figure 15 shows the chamber response to a beam passing through three holes in a cadmium sheet. Each hole was 1 mm in diameter: the first two holes were spaced at 3 mm and the third at 5 mm. Both the 5 mm and 3 mm spacings are completely resolved. The structure within the groups is due to the hole structure of the drift space.

Like the neutron signal, photons will produce electrons in the chamber. The drift space must be constructed of low atomic number materials to minimize these background events. Lead screening will effectively eliminate photons with energies less than 200 keV. Higher energy photons may be filtered out electronically because they will produce electrons that will not trap in the drift space, but give tracks of extended ionization. These cause avalanches on more than one anode wire, and pulses of much slower rise-time (see Fig. 16).

It is expected that various neutron diffraction experiments, e.g. protein crystallography³⁵⁾, will benefit from this two-dimensional detector.

7. FUTURE POSSIBILITIES

The usefulness of the HDPC stems from its two basic properties:

- i) good detection efficiency for non-ionizing radiation because of the high probability of interaction;
- ii) good spatial resolution due to the hole size limitation to the range of the ionizing products.

Advantage may be taken of either or both of these properties, depending on the nature and energy of the radiation.

A problem requiring the first of these properties is the detection of high-energy (GeV) neutral particles. We have made some first steps in this direction at CERN. A chamber has been constructed with a 20 cm thick drift space (Fig. 17),

to contain the electromagnetic shower resulting from photon capture. By backward drifting of the ionization, produced by the shower in the holes in the drift space, the ionization from the vertex of the shower gives the first signal from the chamber. Thus the vertex may be located in two dimensions. The addition of drift time information could enable localization in the third dimension. Unfortunately, although ionization may be drifted through the full 20 cm thickness of the drift space, electron losses are appreciable, and energy resolution (an important parameter for particle physics) was not obtained. A more elaborate scheme with the drift space divided into a number of sections is required.

Use of the second property has already been described for the thermal neutron detector, where conversion is performed separately with a gadolinium foil. Another case where a foil converter (the specimen itself) could be used, is for conversion electron Mössbauer spectroscopy³⁶⁾. Analogous to this are situations where the foil itself contains the radioactive distribution to be measured, e.g. radiochromatography and electrophoresis³⁷⁾.

Clearly the most important applications are those where the drift space provides both particle conversion and spatial resolution, as has been described for gamma-rays. An extension to fast neutrons is natural: the drift space would consist primarily of hydrogenous material for detecting the neutrons by proton recoil. Some interest has been expressed^{38,39)} in the possibility of a detector for solar neutrinos. It has been proposed⁴⁰⁾ that indium should be particularly sensitive to neutrino interactions by inverse beta-decay of ^{115}In to the 614 keV excited state of ^{115}Sn . The signature for the neutrino interaction would be a double or triple delayed coincidence between the prompt electron and the de-excitation photons or internal conversion electrons of ^{115}Sn (see Fig. 18). A large drift space of $\sim 1 \text{ m}^3$ is envisaged. The major problem is to reduce the occurrence of accidental coincidences from the natural activity of ^{115}In , to a level of 10^{-11} ! Spatial correlation in three dimensions of the time-coincident signals would greatly help in this respect.

Some important applications of the high-density proportional chamber have been successfully demonstrated; it is expected that others will appear in the future.

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REFERENCES

- 1) G. Charpak, Annu. Rev. Nuclear Sci. 20, 195 (1970).
- 2) F. Sauli, CERN 77-09 (1977).
- 3) C. Cork, D. Fehr, R. Hamlin, W. Vernon and Ng.H. Xuong, J. Appl. Cryst. 7, 319 (1974).
- 4) R. Allemand, J. Bourdel, E. Roudaut, P. Convert, K. Ible, J. Jacobe, J.P. Cotton and B. Farnoux, Nuclear Instrum. Methods 126, 29 (1975).
- 5) J. Alberi, J. Fischer, V. Radeka, L.C. Rogers and B. Schoenborn, IEEE Trans. Nuclear Sci. NS-22, 255 (1975).
- 6) S.N. Kaplan, L. Kaufman, V. Perez-Mendez and K. Valentine, Nuclear Instrum. Methods 106, 397 (1973).
- 7) S.E. Derenzo, T.F. Budinger, R.G. Smits, H. Zaklad and L.W. Alvarez, Proc. Symposium on Advanced Technology Arising from Particle Physics Research, Argonne, 1973 (ANL 8080, Argonne, Ill., 1973), p. 11.1.
- 8) A.P. Jeavons, G. Charpak and R. Stubbs, Nuclear Instrum. Methods 124, 491 (1975).
- 9) A.P. Jeavons and C. Cate, IEEE Trans. Nuclear Sci. NS-23, 640 (1976).
- 10) H. Slatis, Ark. Matematik, Astronomi o. Fysik 36A, No. 17 (1949).
- 11) H. Slatis, Rev. Sci. Instrum. 20, No. 5, 353 (1949).
- 12) C.B. Lim, D. Chu, L. Kaufman, V. Perez-Mendez and J. Sperinde, IEEE Trans. Nuclear Sci. 21, 85 (1974).
- 13) C.J. Borkowski and M.K. Kopp, IEEE Trans. Nuclear Sci. 17, 340 (1970).
- 14) V. Perez-Mendez and S.I. Parker, IEEE Trans. Nuclear Sci. 21, 45 (1974).
- 15) W.R. Kuhlmann, K.H. Lauterjung, B. Schimmer and K. Sistemich, Nuclear Instrum. Methods 40, 118 (1966).
- 16) G. Charpak, A.P. Jeavons, F. Sauli and R.J. Stubbs, CERN 73-11 (1973).
- 17) C. Parkman, Z. Hajduk, A.P. Jeavons, N. Ford and B. Lindberg, Proc. 2nd Nuclear Electronics Symp., Ispra (Euratom, Ispra, 1975), report EUR 5370e, p. 139.
- 18) A.P. Jeavons, N.L. Ford, B. Lindberg, C. Parkman and Z. Hajduk, IEEE Trans. Nuclear Sci. NS-23, 259 (1976).
- 19) V. Radeka, IEEE Trans. Nuclear Sci. 21, 51 (1974).
- 20) J. Mader, S. Berko, H. Krakauer and A. Bansil, Phys. Rev. Letters 37, 1232 (1976).
- 21) A.P. Jeavons and A. Manuel, Presented at the 4th Internat. Conf. on Positron Annihilation, Helsingor, Denmark (1976) (unpublished).
- 22) A.P. Jeavons, D.W. Townsend, N.L. Ford, K. Kull, A. Manuel, O. Fischer and M. Peter, IEEE Trans. Nuclear Sci. NS-25, 164 (1978).

- 23) A. Manuel, O. Fischer, M. Peter and A.P. Jeavons, presented at this conference.
- 24) Z.H. Cho, M.B. Cohen, M. Singh, L. Eriksson, J. Chan, N. MacDonald and L. Spolter, IEEE Trans. Nuclear Sci. NS-24, 532 (1977).
- 25) C.A. Burnham and G.L. Brownell, IEEE Trans. Nuclear Sci. NS-19, 201 (1972).
- 26) E.J. Hoffman, M.E. Phelps, N.A. Mullani, C.S. Higgins and M.M. Ter-Pogossian, J. Nuclear Med. 17, 493 (1976).
- 27) S.E. Derenzo, T.F. Budinger, J.L. Cahoon, R.H. Huesman and H.G. Jackson, IEEE Trans. Nuclear Sci. NS-24, 544 (1977).
- 28) G. Muehllehner, M.P. Buchin and J.H. Dudek, IEEE Trans. Nuclear Sci. NS-23, 528 (1976).
- 29) C.B. Lim, D. Chu, L. Kaufman, V. Perez-Mendez, R. Hattner and D.C. Price, IEEE Trans. Nuclear Sci. NS-22, 388 (1975).
- 30) R.S. Hattner, C.B. Lim, S.J. Swann, L. Kaufman, V. Perez-Mendez, D. Chu, J.P. Huberty, D.C. Price and C.B. Wilson, IEEE Trans. Nuclear Sci. NS-23, 523 (1976).
- 31) L.T. Chang, B. MacDonald and V. Perez-Mendez, LBL-3872 (1975).
- 32) D.W. Townsend, C. Piney and A.P. Jeavons, Phys. Med. Biol. 23, 235 (1978).
- 33) G. Chu and K. Tam, Phys. Med. Biol. 22, 245 (1977).
- 34) A.P. Jeavons, N.L. Ford, B. Lindberg and R. Sachot, CERN 77-01 (1977) and Nuclear Instrum. Methods 148, 29 (1978).
- 35) H.D. Bartunik, Institut Laue-Langevin Internal Scientific Report ILL 75M42, 122 (1975).
- 36) J. Spijkerman, *in* Mössbauer Effect Methodology (ed. I.J. Gruverman) (Plenum Press, New York, 1971), Vol. 7, p. 85.
- 37) F. Berthold and M. Wenzel, *in* Instrumentation in nuclear medicine (ed. G.J. Hine) (Academic Press, New York, 1967), Vol. 1, p. 251.
- 38) R.S. Raghavan, Bell Laboratories, private communication.
- 39) V. Radeka, Brookhaven National Lab., private communication.
- 40) R.S. Raghavan, Phys. Rev. Letters 37, 259 (1976).

Figure captions

- Fig. 1 : The principle of the HDPC for photon detection. Photons are captured in the solid bars and produce fast electrons which can escape to an adjacent hole. The free electrons resulting from gas ionization in the hole may be extracted by an electric drift field, and detected by a proportional chamber.
- Fig. 2 : Two different methods, tried at CERN, for making a photon converter:
a) a bundle of glass tubes;
b) a stack of alternate conducting (copper) and insulating (mylar) grids.
- Fig. 3 : An early realization of the conducting-insulating layer construction with a proportional counter. Concentric rings of lead surround the anode wire. (See Refs. 10 and 11 for details.)
- Fig. 4 : An extension of the layer construction of Fig. 3 to the proportional chamber: the honeycomb converter. (See Ref. 12.)
- Fig. 5 : The principle of centre-of-cluster read-out. Threshold discriminators and priority encoders find the end channels (X1, X2) of the pulse distribution on the cathode plane. The centre (X) is then calculated by hardware in ~ 100 nsec.
- Fig. 6 : A general view of one of the two chambers forming the positron camera.
- Fig. 7 : The spatial resolution obtained from a chamber with 660 keV gamma-rays collimated by a 0.5 mm slit.
- Fig. 8 : The coincidence resolving time of the new, 10% efficient, bismuth-doped araldite converter. The best resolving time, 100 nsec, is obtained with carbon-dioxide gas and a high drift field $\sim 10^4$ V cm⁻¹.
- Fig. 9 : The spherical Fermi surface of aluminium obtained from the measurement of the angular correlation of positron annihilation radiation.

Detailed structure is also revealed. Horizontal axes: x-angle against y-angle. Vertical axis: number of events. Grid size: 0.5×0.5 mrad; total number of events: 3×10^6 ; number of events at the peak of the distribution: 5000.

- Fig. 10 : The schematic layout of the positron camera. Images may be obtained on a number of planes between and parallel to the detectors. Mathematical reconstruction can separate the superimposed plane activities.
- Fig. 11 : The experimentally measured camera point-spread function for a) air and b) water. Angular acceptance: $\pm 25^\circ$.
- Fig. 12 : Image sections through a mouse, following an injection of $5.7 \mu\text{Ci}$ of ^{18}F . The left-hand column is the raw data: the focused tomograms. The right-hand column shows the reconstructed sections after nine-point smoothing, Fourier deconvolution using singular-value-decomposition, and background subtraction. Bone structure is clearly revealed. The high spot at the base of the spine is due to kidney uptake of ^{18}F . Bin size 1×1 mm; sections spaced at 10 mm; 4×10^5 events.
- Fig. 13 : An X-ray photograph of the mouse secured in its cage, for comparison with Fig. 12.
- Fig. 14 : A thermal neutron detector, using a gadolinium foil converter and a high-density drift space.
- Fig. 15 : An image cross-section of three parallel neutron beams. There are four bins per millimetre.
- Fig. 16 : The pulse rise-time spectrum from the neutron detector. Full scale 100 nsec: a) with neutrons, b) without neutrons.
- Fig. 17 : A high-density proportional chamber for localizing GeV electromagnetic showers. The depth of the lead-plate drift space is 20 cm.
- Fig. 18 : Nuclear data for ^{115}In and ^{115}Sn .

Fig. 1

a)

b)

Fig. 2

Fig. 3

Fig. 4

$$X = (N - X_2) + \frac{X_1 - (N - X_2)}{2} = \frac{N + X_1 - X_2}{2}$$

Fig. 5

Fig. 6

Isobutane, 5 kV drift, 150 nsec FWHM

Isobutane, 8 kV drift, 150 nsec FWHM

Carbon dioxide, 5 kV drift, 200 nsec FWHM

Carbon dioxide, 8 kV drift, 100 nsec FWHM

Fig. 8

Fig. 7

Fig. 9

Fig. 10

Fig. 11

Fig. 13

Fig. 14

Fig. 15

a. with neutrons

b. without neutrons

Fig. 16

Fig. 17

Fig. 18