output of the PM tube that can be sent to an electronic counter just as for a Geiger tube. Solid scintillators are much more dense than the gas of a Geiger counter, and so are much more efficient detectors—especially for γ rays, which interact less with matter than do β rays. Scintillators that can measure the total energy deposited are much used today and are called **calorimeters**.

Calorimeter

In tracer work (Section 31–7), **liquid scintillators** are often used. Radioactive samples taken at different times or from different parts of an organism are placed directly in small bottles containing the liquid scintillator. This is particularly convenient for detection of β rays from $^{3}_{1}H$ and $^{14}_{6}C$, which have very low energies and have difficulty passing through the outer covering of a crystal scintillator or Geiger tube. A PM tube is still used to produce the electric signal.

Semiconductor detector (pn junction)

A **semiconductor detector** consists of a reverse-biased *pn* junction diode (Section 29–8). A particle passing through the junction can excite electrons into the conduction band, leaving holes in the valence band. The freed charges produce a short electrical pulse that can be counted just as for Geiger and scintillation counters. Silicon wafer semiconductors have their surface etched into tiny pixels, thus providing detailed particle position information.

Hospital workers and others who work around radiation carry *film badges* which detect the accumulation of radiation. The film inside is periodically replaced and developed, the darkness being related to total exposure (see Section 31–5).

Emulsions

The devices discussed so far are used for counting the number of particles (or decays of a radioactive isotope). Other devices allow the track of charged particles to be *seen*. The simplest is the **photographic emulsion**, which can be small and portable, used now particularly for cosmic-ray studies from balloons. A charged particle passing through a layer of photographic emulsion ionizes the atoms along its path. These points undergo a chemical change, and when the emulsion is developed the particle's path is revealed. (One type of neutrino, τ, was indirectly discovered using an emulsion at Fermilab; see Chapter 32.)

Cloud chamber

In a **cloud chamber**, a gas is cooled to a temperature slightly below its usual condensation point ("supercooled"), and gas molecules condense on any ionized molecules present. Ions produced when a charged particle passes through serve as centers on which tiny droplets form (Fig. 30–15). Light scatters more from these droplets than from the gas background, so a photo of the cloud chamber at the right moment shows the track of the particle. An important instrument in the early days of nuclear physics, it is little used today.

Bubble chamber

The **bubble chamber**, invented in 1952 by D. A. Glaser (1926–   ), makes use of a superheated liquid kept close to its normal boiling point. The bubbles characteristic of boiling form around ions produced by the passage of a charged particle. A photograph of the interior of the chamber reveals paths of particles that recently passed through. Because the bubble chamber uses a liquid, often liquid hydrogen, it is a much more efficient device than a cloud chamber for observing the tracks of charged particles and their interactions with the nuclei of the liquid. A magnetic field is usually applied across the chamber and the momentum of the moving particles can be determined from the radius of curvature of their paths.

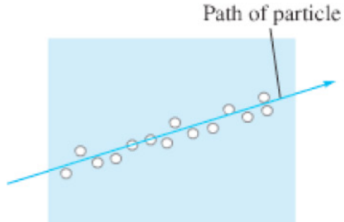

FIGURE 30–15 In a cloud or bubble chamber, droplets or bubbles are formed around ions produced by the passage of a charged particle.