which reduces to a quadratic equation in \( \tau \) with the solution

\[
\tau = \frac{1 \pm \sqrt{1 - R_{12}'(R_1' + R_2' - R_{12}')/R_1'R_2'}}{R_{12}'}.
\]

This can be expanded in the small quantity \((R_1' + R_2' - R_{12}')\) to give the approximate expression

\[
\tau \approx \frac{(R_1' + R_2' - R_{12}')}{{2R_1'R_2'}}. \quad (8.41)
\]

We now apply Eq. (8.41) to data obtained by students with the same counter used for Fig. 8.19. In practice, source \( S_1 \) is first brought to the vicinity of the counter and \( R_1' \) is obtained, next \( S_2 \) is also brought in the area and \( R_{12}' \) is obtained, and finally \( S_1 \) is removed and \( R_2' \) is measured: thus no uncertainties due to source position can arise. They obtain

\[
R_1' = 395 \pm 3 \text{ counts/s} \\
R_{12}' = 655 \pm 3 \text{ counts/s} \\
R_2' = 334 \pm 3 \text{ counts/s},
\]

yielding \( \tau = 282 \pm 20 \mu s \), in better agreement with Eq. (8.40) than with Eq. (8.39).

The rather long dead time of the Geiger counter is a serious limitation restricting its use when high counting rates are involved; the ionization counter and proportional counter have dead times several orders of magnitude shorter.

8.4. THE SCINTILLATION COUNTER

8.4.1. General

As we saw, in gaseous-ionization instruments, the electron–ion pairs were directly collected; in the scintillation counter the ionization produced by the passage of a charged particle is detected by the emission of weak scintillations as the excited molecules of the detector return to the ground state. The fact that certain materials emit scintillations when traversed or struck by charged particles has been known for a long time, Rutherford being the first to use a ZnS screen in his alpha particle scattering experiments.
The scintillation counters used currently were developed in the 1950s and consist of an organic or inorganic crystal coupled to a sensitive photomultiplier that responds to the light pulses. Anthracene or stilbene crystals make excellent scintillators, but organic compounds embedded in transparent plastic, such as polystyrene, are now widely used because of ease in handling and machining and availability in large sizes. Such materials are commercially available under the general description of “plastic scintillators.” The active materials are compounds, such as “PPO,” 2-5-diphenyloxazole, or diphenylstilbene, or others, and are also available in liquid form.

Organic scintillators have an extremely fast response, on the order of $10^{-9}$ s, which can be matched by good photomultipliers. On the other hand, because of the low density and low Z, their efficiency for gamma-ray conversion is not high. To detect gamma rays, inorganic crystals, such as NaI or CsI, are used instead, activated with some impurity, for instance Tl (1 part in $10^3$). Inorganic crystals have an excellent efficiency for gamma-ray conversion, due to their high Z; from Eq. (8.20) we recall that the photoelectric effect is proportional to $Z^5$ and from Eq. (8.23) pair production is proportional to $Z^2$. However, the light output from inorganic crystals is spread over a much longer time interval, on the order of $10^{-6}$ s. Such inorganic crystals are also available commercially, appropriately encased since they are damaged by humidity; they come in sizes up to several cubic inches.

The light output of scintillators is proportional (as a matter of fact, linear) to the energy lost by the particle that traverses the detector; thus, by pulse-height analyzing the electrical output of the photomultiplier, the scintillation counter may be used as a spectrometer. This procedure is discussed in detail in the following section, where it is seen that energy resolution on the order of 10% or better is achievable.

The mechanism of emission of the photons in the scintillator material is rather involved. Table 8.2 gives a chart of the processes involved in the emission of light in organic and inorganic crystals. In inorganic materials it is the migration of the electrons through the lattice (until they excite an impurity center) that is responsible for the long duration of the light pulse.

Even though the efficiency for transferring the energy lost by ionization to the photons in the visible region is on the average low, $\epsilon \approx 1.5\%$, a scintillator still provides ample light output. Consider the case of a plastic scintillator 1-cm thick, traversed by a minimum-ionizing particle: $dE/dx = 2 \times 10^6$ eV per g/cm$^2$; if we take the average photon energy

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31 For example, from Pilot Chemicals Inc., 36 Pleasant St., Watertown, MA.
32 For example, from Harshaw Chemical Corp., Cleveland, OH.
<table>
<thead>
<tr>
<th>Inorganic scintillator</th>
<th>Organic scintillator</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Impurity activated)</td>
<td></td>
</tr>
<tr>
<td>Holes</td>
<td>Electrons</td>
</tr>
<tr>
<td>Drift to impurity center and ionize it. Emission of thermal radiation</td>
<td></td>
</tr>
<tr>
<td>Ionized impurity center (\rightarrow) Capture with emission of thermal radiation</td>
<td></td>
</tr>
<tr>
<td>Excited impurity center</td>
<td></td>
</tr>
<tr>
<td>Electron drops into metastable state of impurity center</td>
<td></td>
</tr>
<tr>
<td>Radiationless transition</td>
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</tbody>
</table>

as 3 eV, we obtain $10^4$ photons. The efficiency of a photomultiplier cathode for converting photons into electrons is on the order of 0.1, and the geometric efficiency for collecting the photons onto the photocathode is usually high, so that on the order of 1000 electrons are released. With modern techniques, however, it is possible to detect the release of a few photoelectrons, or even of a single one.

Clearly the scintillator material must be transparent to the visible radiation and optical coupling to the photomultiplier must be provided. This is achieved either directly or through a “lightpipe,” which is an appropriately shaped piece of lucite or other medium of high refractive index that traps and guides the light due to total internal reflection at its surfaces. At the surfaces where the lightpipe is joined to the scintillator or to the photomultiplier, optical contact is achieved by the use of either viscous fluids or special glues.33 Obviously the whole assembly must be light tight; this is frequently achieved by wrapping black electrical tape around the scintillator, lightpipe, and phototube.

Because of its great stability and ease of operation, as well as because of its time and energy resolution, the scintillation counter has become the most frequently used detector in nuclear physics, especially for high-energy particles.

8.4.2. Experiment on the Determination of the Energy of Gamma Rays with a Scintillation Counter

If atoms are quantum-mechanical systems and a typical manifestation of this fact is the emission of spectral lines of light, it should be expected that nuclei, when excited, would emit similar line spectra.

Since the nuclear radius is three to five orders of magnitude smaller than that of atoms, the forces that bind the nucleus (against the repulsion of the positive charges confined in its volume) must be correspondingly stronger than the forces that bind the atomic electrons to the nucleus. As a consequence, the energy levels and the quanta of energy emitted in a nuclear transition are also orders of magnitudes larger than those of atomic transitions. Indeed, the quanta of electromagnetic radiation emitted in a nuclear transition fall in the gamma-ray region, and new techniques are needed for their detection and for the measurement of their (wavelength) energy.

33 In the first category, Corning 200,000 centipoise fluid or clear vacuum grease; in the latter, R 363, PS 28 acrylic glue, etc.
Further, because of the larger spacing between energy levels, it is not easy to excite a nucleus from its ground state by the simple means of electric discharges or arc sources such as are used for atoms; instead, beams of neutrons or high-energy gamma rays, or high-energy charged particles, are required. However, in distinction to atomic transitions where the de-excitation probability is on the order of $10^8/s$, some nuclear transitions have a very small "decay" probability, as small as $10^{-7}/s$, corresponding to a lifetime of 100 days. Thus, it is possible to excite a sample of nuclei inside a nuclear reactor, or by subjecting them to cyclotron bombardment, or by other means, and subsequently bring them to the laboratory for measuring their spectrum or for other uses. Indeed, some of the nuclei that have very long lifetimes can be found in nature in their excited state; these are the naturally radioactive elements.

We now know that the appropriate detector for measurements of the energy of gamma rays is an inorganic crystal. When a gamma ray of energy $<1$ MeV enters the detector, it will interact either by the photoelectric effect or the Compton effect. In the former case it is fair to assume that the ejected photoelectron will deposit all its energy in the scintillator; in the Compton effect, however, the scattered photon may or may not convert in the scintillator (depending on the size and geometry of the detector).

The pulse-height spectrum for gamma rays of a given energy will consist of a peak at an energy corresponding to that of the gamma ray and a continuum below the peak, corresponding to Compton-scattered gamma rays that escaped from the crystal before totally converting. This can be seen in Fig. 8.20 and those that follow. Clearly the larger the size of the crystal, the larger the percentage of the output counts that will lie in the photopeak; thus, the gamma-ray line will become more pronounced.

Most of the data reported here were obtained with a NaI–Tl activated crystal,34 2 in. in diameter and 2 in. wide, coupled directly to a photomultiplier tube.35 (Photomultiplier tubes and high-voltage bias schemes are discussed in Appendix E.2.) The output pulse is fed to an Ortec36 Model 570 amplifier, and its output is fed to a Canberra multiport multichannel analyzer (MCA). The MCA is controlled and read out through a

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35The crystal and photomultiplier tube assembly is a commercial package from Canberra Industries, http://www.canberra.com/, Model 802-3. The photomultiplier tube "base" was constructed from a commercial socket and simple components.
36http://www.ortec-online.com/.
FIGURE 8.20 Pulse-height spectrum of $^{60}$Co gamma rays obtained with a NaI crystal, along with the decay scheme of $^{60}$Co. The upper spectrum was taken with a 2-in.-diameter crystal detector, while the bottom was taken with a 3-in. crystal. The $^{60}$Co source was relatively weak (less than 1 μCi when these data were taken) and the source-to-detector distance was 10 cm. The decay scheme is also shown.
GPIB interface, in this case using a laptop computer. Spectra acquired in this way are histograms with $8192 = 2^{13}$ bins. (Adjacent bins were added together to reduce the statistical fluctuations from bin to bin. This is easy to do with the reshape command in MATLAB.) The conversion of bin number to photon energy depends on the combined gain of the photomultiplier and the amplifier, and must be calibrated with sources of known photon energy.

The following figures give the results obtained by a student. Figure 8.20 gives the spectrum of $^{60}\text{Co}$ and shows two distinct peaks, which we attribute to gamma rays emitted in the de-excitation of $^{60}\text{Ni}$ from its 2.505-MeV level to the 1.333-MeV level, and from that level to the ground state according to the decay scheme also shown in the figure. For comparison, we also show a spectrum taken with a 3-in.-diameter and 3-in.-wide crystal. As a measure of the energy resolution, we may consider the full-width of the peak at half-maximum, which is on the order of 480 channels, hence a resolution of $480/6000 \approx 8\%$. We also notice a significant background for pulse heights lower than that of the peaks, which is due to Compton-scattered gamma rays that subsequently escaped from the crystal. This background is much less severe for the larger crystal.

Figure 8.21 gives similar data for a sample of $^{137}\text{Cs}$; here the 0.662-MeV gamma ray represents the de-excitation of $^{137}\text{Ba}$. Again we notice some Compton background and an energy resolution on the order of 10%. Figures 8.22 and 8.23 give the pulse-height spectra from $^{22}\text{Na}$ and $^{133}\text{Ba}$, respectively. For the $^{22}\text{Na}$, the peak at 1.277 MeV arises from the de-excitation of $^{22}\text{Ne}$; the larger peak at 0.511 MeV arises from annihilation radiation. Indeed, from the level diagram of $^{22}\text{Na}$ decay, we notice that
FIGURE 8.21 Pulse-height spectrum of $^{137}$Cs gamma rays obtained with a NaI crystal, and the associated decay scheme.
FIGURE 8.22  Pulse-height spectrum of $^{22}$Na gamma rays obtained with a NaI crystal, and the associated decay scheme. Note that the 511-KeV line is due to positron annihilation.
positrons are emitted; the positrons are usually stopped in the walls of the source container, or in the crystal face, and as they come close enough to an electron they annihilate into two gamma rays, each gamma ray sharing the energy of the electron–positron pair.\footnote{See also the detailed discussion in Chapter 9.} It is one\footnote{Note that they are emitted with a relative angle of 180°.} of these gamma rays that is then converted in the crystal and gives rise to the 0.511-MeV peak.

Finally, in Fig. 8.24 is given a plot of all the observed peaks against channel number, showing the linearity of pulse height against energy. (MATLAB provides a useful utility command, ginput, for interactively identifying the peak position in spectrum plots using the cursor on your computer.) In addition to the gamma rays, the nuclei investigated also emit beta rays, and one would expect to see the corresponding peaks in the pulse-height spectrum. This, however, is not true because the beta spectrum is continuous instead of being a sharp line as is the case with gamma-ray spectra; in addition, electrons may lose variable amounts of energy before reaching the scintillation crystal, so that unless special precautions are taken, the energy resolution is usually poor.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure8_23.png}
\caption{Pulse-height spectrum of $^{133}$Ba gamma rays obtained with a NaI crystal. The decay scheme is complicated, but the most dominant $\gamma$ rays at high energy are at 356 and 302 keV.}
\end{figure}
In interpreting gamma-ray spectra some care must be taken since spurious peaks due to instrumental effects or physical effects do appear. First, there can be peaks arising from the emission of X-rays, following photoejection of K-shell electrons either in the source or in the shielding. Also, a peak may appear due to photons that backscatter (by 180°) in the photomultiplier window or elsewhere; then the Compton-scattered electron escapes, but the scattered photon becomes converted in the crystal. For $^{137}$Cs with its 0.662-MeV gamma ray, the backscattering peak appears at 0.185 MeV and can be identified in a carefully measured spectrum.

Another spurious effect occurs when an incoming photon of energy $E$ ejects a K-shell electron from the iodine of the crystal, but the emitted X-ray escapes without converting in the detector. The ejected photoelectron has an energy

$$E - E_K,$$

where $E_K$ is the energy of the K shell of iodine, namely, 29 keV, and will give rise to a peak not coinciding with the true photopeak. This so-called
"escape-peak" can be identified because it is located 29 keV below the photopeak; it is most pronounced in the pulse-height spectra of low-energy gamma rays.

The relative ratio of counts in the photopeak as compared to the counts in the Compton background depends on the crystal and source geometry and on the gamma-ray energy. Usually the relative counts in the photopeak give sufficient information, but when the absolute number of gamma rays is required, we must calculate the efficiency of the crystal for the particular geometry and gamma-ray energy. Extensive tables of efficiency for most combinations of the relevant parameters have been calculated.  

8.5. SOLID-STATE DETECTORS

8.5.1. General

We have seen how the gaseous ionization counters and the scintillation counters are widely used for the detection of radiation and charged particles. It is also possible to use semiconductor materials for the detection of charged particles, especially those of low energy; such detectors are appropriately referred to as "solid-state counters." 40

In a general sense, we can think of this type of detector as a solid-state ionization chamber, having two basic advantages over a gas-filled ionization chamber:

(a) The energy required for the creation of an electron–ion pair is 3 eV (as compared to approximately 30 eV in a gas) so that stronger signals and better statistics can be achieved.

(b) The stopping power is approximately $10^3$ times that of a gas-filled device (since the detector material is so much denser), and thus it becomes possible to stop, in the detector, particles with energies typical of nuclear interactions. Consequently a very large number of electron–ion pairs are formed, leading to very good energy resolution. A 1-MeV proton stopping in a solid-state detector will create 300,000 electron–ion pairs, while the same proton traversing a proportional counter of 2-cm thickness would only release approximately 30 pairs.

40 The scintillation counter is also a detector in the solid state!