IV. SOURCES OF ELECTROMAGNETIC RADIATION

A. Gamma Rays Following Beta Decay
Gamma radiation is emitted by excited nuclei in their transition to lower-lying nuclear levels. In most practical laboratory sources, the excited nuclear states are created in the decay of a parent radionuclide. Four common examples which are widely used as gamma ray calibration sources are illustrated in the decay schemes in Fig. 1-5. In each case, a form of beta decay leads to the population of the excited state in the daughter nucleus. For the examples shown, the beta decay is a relatively slow process characterized by a half-life of hundreds of days or greater, whereas the excited states in the daughter nucleus have a much shorter average lifetime (typically of the order of nanoseconds or less). De-excitation takes place through the emission of a gamma ray photon whose energy is essentially equal to the difference in energy between the initial and final nuclear states. The gamma rays therefore appear with a half-life characteristic of the parent beta decay, but with an energy that reflects the energy level structure of the daughter nucleus. For example, although $^{60}$Co gamma rays do not decrease in intensity with the 5.26 year half-life characteristic of $^{60}$Co, they actually arise from transitions in the $^{60}$Ni nucleus. Decay schemes of the type shown in Fig. 1-5 are compiled for all radioactive nuclei in Ref. 1. From the probabilities of various de-excitation transitions (or “branching ratios”) given in these decay schemes, the number of gamma ray photons per disintegration of the parent nucleus can be deduced. Some specific radionuclide gamma ray sources useful in the precise energy calibration and efficiency calibration of gamma ray detectors are listed in Tables 12-1 and 12-2.

Because nuclear states have very well-defined energies, the energies of gamma rays emitted in state-to-state transitions are also very specific. The gamma rays from any one transition are nearly monoenergetic, and the inherent line width of the photon energy distribution is always small compared with the energy resolution of any of the detectors described later in this text. A measurement of the detector response is therefore indicative of its own limiting resolution rather than any variation in the incident gamma ray energy.*

The common gamma ray sources based on beta decay are generally limited to energies below about 2.8 MeV. One nuclide, $^{56}$Co, has gained recent attention as a potential source for gamma rays of higher energy. The decay scheme of this isotope, which proceeds both by electron capture and beta-plus decay, gives rise to a complex spectrum of gamma rays whose energies extend to as high as 3.55 MeV. However, its short half-life of 77 days largely limits its use to facilities with access to accelerators necessary to carry out its production through the $^{56}$Fe(p, n) reaction.

* A rare exception may occur if the emitting nuclei have large velocities. The Doppler effect can then introduce an energy spread that may be significant in detectors with excellent energy resolution. An example is given later in this chapter in which gamma rays are emitted from nuclei that are still moving after being formed in a nuclear reaction.
Gamma ray reference sources are an essential accessory in any radiation measurements laboratory in which gamma ray measurements are carried out. They normally consist of samples of radioisotopes of a few microcuries (around $10^5$ Bq) encased in plastic discs or rods. The thickness of the encapsulation is generally large enough to stop any particulate radiation from the decay of the parent nucleus, and the only primary radiation emerging from the surface is the gamma radiation produced in the daughter decay. However, secondary radiations such as annihilation photons or bremsstrahlung can be significant at times (see below). Although the radiation hazard of such sources is minimal, the gamma ray emission rate is sufficiently high to permit ready energy calibration of most types of gamma ray detectors.

If the sources are to be used to carry out accurate efficiency calibration as well, their absolute activity must also be known. In these cases, the radioisotope deposits are generally prepared on much thinner backings with a minimum of...
overlying cover to reduce gamma ray attenuation and scattering within the source. External absorbers must then be used to eliminate any particulate emission if its presence will interfere with the application.

B. Annihilation Radiation
When the parent nucleus undergoes beta-plus decay, additional electromagnetic radiation is generated. The origin lies in the fate of the positrons emitted in the primary decay process. Because they generally travel only a few millimeters before losing their kinetic energy (see Chapter 2), the inherent encapsulation around the source is often sufficiently thick to fully stop the positrons. When their energy is very low, near the end of their range, they combine with normal negative electrons in the absorbing materials in the process of annihilation.* The original positron and electron disappear and are replaced by two oppositely directed 0.511 MeV electromagnetic photons known as annihilation radiation. This radiation is then superimposed on whatever gamma radiation may be emitted in the subsequent decay of the daughter product. For example, in the decay of $^{22}\text{Na}$, shown in Fig. 1-5, photons of both 0.511 and 1.274 MeV energy are emitted from encapsulated sources.

C. Gamma Rays Following Nuclear Reactions
If gamma rays with energies higher than those available from beta-active isotopes are needed, some other process must lead to the population of higher-lying nuclear states. One possibility is the following nuclear reaction

$$^{4}\alpha + ^{2}\text{Be} \rightarrow ^{12}\text{C}^{*} + ^{1}\text{n}$$

where the product nucleus $^{12}\text{C}$ is left in an excited state. Its decay gives rise to a gamma ray photon of 4.44 MeV energy. Unfortunately, the average lifetime of this state is so short that the recoil carbon atom does not have time to come to rest before the gamma ray is emitted. The resulting photon energies are therefore broadened by Doppler effects, depending on the relative orientation of the recoil atom velocity and the photon direction, and there is an inherent spread of about 1 percent in the gamma ray energies. This line width is adequate for many calibration purposes, but it is too large for detectors with very good energy resolution (such as the Ge(Li) detectors of Chapter 12).

Another possibility is the reaction

$$^{4}\alpha + ^{16}\text{O} \rightarrow ^{16}\text{O}^{*} + ^{1}\text{n}$$

Here the product nucleus $^{16}\text{O}$ can be formed in an excited state at 6.130 MeV above the ground state and with a lifetime of about $2 \times 10^{-11}$ s. This lifetime is

*This step can take place either directly or through an intermediate stage in which the positron and electron form a quasistable combination, known as positronium, which may exist for a fraction of a microsecond.
sufficiently long to eliminate almost all Doppler effects, and the resulting 6.130 MeV gamma ray photons are essentially monoenergetic.

Both the above reactions can be exploited by combining a radioisotope which decays by alpha emission with the appropriate target material (either $^9\text{Be}$ or $^{13}\text{C}$). Because sources of this type are more commonly used to produce neutrons, further discussion of the choice of alpha emitter and other aspects of the source design will be postponed until the following section on neutron sources. Because most alpha particles do not lead to a reaction before losing their energy in the target material, large activities of the alpha emitter must be used to produce a gamma ray source of practical intensity. For example, about $3 \times 10^9$ Bq (90 mCi) of $^{244}\text{Cm}$ is required when mixed with isotopically separated $^{13}\text{C}$ to produce $3.7 \times 10^3$ gamma rays per second$^7$.

D. Bremsstrahlung

When fast electrons interact in matter, part of their energy is converted into electromagnetic radiation in the form of bremsstrahlung. (This process is discussed in somewhat more detail in Chapter 2.) The fraction of the electron

FIGURE 1-6. The bremsstrahlung energy spectrum emitted in the forward direction by 5.3 MeV electrons incident on a Au-W target. A 7.72 g/cm$^2$ aluminum filter also was present. (From Ferdinande, et al$^8$.)

19
FIGURE 1-7. Examples of measured pulse height spectra (using a NaI(Tl) scintillator) after filtration of an X-ray tube output using the indicated absorbers and tube voltages. (From Storm, Lier, and Israel9.)
energy converted into bremsstrahlung increases with increasing electron energy and is largest for absorbing materials of high atomic number. The process is important in the production of X-rays from conventional X-ray tubes.

For monoenergetic electrons that slow down and stop in a given material, the bremsstrahlung energy spectrum is a continuum with photon energies which extend as high as the electron energy itself. The shape of a typical spectrum produced by monoenergetic electrons is shown in Fig. 1-6. The emission of low energy photons predominates, and the average photon energy is a small fraction of the incident electron energy. Because these spectra are continua, they cannot be directly applied to the energy calibration of radiation detectors.

The shape of the energy spectrum from an X-ray tube can be beneficially altered by filtration or passage through appropriate absorber materials. Through the use of absorbers which preferentially remove the lower energy photons, a peaked spectrum can be produced which, although far from monoenergetic, can be useful in the energy calibration of detectors whose response changes only gradually with energy. Some examples of filtered spectra from X-ray tubes are plotted in Fig. 1-7. At lower energies, the abrupt change in filter transmission at its K-absorption edge (see Chapter 2) can produce a prominent peak at the corresponding energy in the filtered spectrum.

Bremsstrahlung is also produced by other sources of fast electrons, including beta particles. Therefore, some bremsstrahlung photons are generated by any beta-active isotope which is encapsulated to stop the beta particles. Some examples of bremsstrahlung spectra from specific isotopes are plotted in Fig. 10-5.

In addition to bremsstrahlung, characteristic X-rays (see following section) are also produced when fast electrons pass through an absorber. Therefore, the spectra from X-ray tubes or other bremsstrahlung sources also show characteristic X-ray emission lines superimposed on the continuous bremsstrahlung spectrum.

E. Characteristic X-Rays

If the orbital electrons in an atom are disrupted from their normal configuration by some excitation process, the atom may exist in an excited state for a short period of time. There is a natural tendency for the electrons to rearrange themselves to return the atom to its lowest energy or ground state within a time which is characteristically a nanosecond or less in a solid material. The energy liberated in the transition from the excited to the ground state takes the form of a characteristic X-ray photon whose energy is given by the energy difference between the initial and final states. For example, if a vacancy is temporarily created in the K shell of an atom, then a characteristic K X-ray is liberated when that vacancy is subsequently filled. If that electron comes from the L shell, then a K\textsubscript{α} photon is produced whose energy is equal to the difference in binding energies between the K and L shells. If the filling electron originated in the M
shell instead, then a $K_\beta$ photon is produced with slightly larger energy, and so on. The maximum K-series photon is produced when the vacancy is filled by a free or unbound electron, and the corresponding photon energy is then simply given by the K shell binding energy. Vacancies created in outer shells by the filling of a K shell vacancy are subsequently filled with the emission of L, M, . . . series characteristic X-rays.

Because their energy is greatest, the K-series X-rays are generally of most practical significance. Their energy increases regularly with atomic number of the element, and is, for example, about 1 keV for sodium with $Z = 11$, 10 keV for gallium with $Z = 31$, and 100 keV for radium with $Z = 88$. The L series X-rays do not reach 1 keV until $Z = 28$ and 10 keV at $Z = 74$. Extensive tables of precise characteristic X-ray energies can be found in reference 1. Because the energy of the characteristic X-rays is unique to each individual element, they are often used in the elemental analysis of unknown samples (see Fig. 13-15).

For an atom in an excited state, the ejection of an Auger electron is a competitive process to the emission of characteristic X-rays. The fluorescent yield is defined as the fraction of all cases in which the excited atom emits a characteristic X-ray photon in its de-excitation. Values for the fluorescent yield are often tabulated as part of spectroscopic data.

A large number of different physical processes can lead to the population of excited atomic states from which characteristic X-rays originate. In general, the relative yields of the K, L, and subsequent series will depend on the excitation method, but the energy of the characteristic photons is fixed by the basic atomic binding energies. We will list below those excitation mechanisms that are of most practical importance for compact laboratory sources of characteristic X-rays.

1. EXCITATION BY RADIOACTIVE DECAY

In the nuclear decay process of electron capture, the nuclear charge is decreased by one unit by the capture of an orbital electron, most often a K-electron. The resulting atom still has the right number of orbital electrons, but the capture process has created a vacancy in one of the inner shells. When this vacancy is subsequently filled, X-rays are generated which are characteristic of the product element. The decay may populate either the ground state or an excited state in the product nucleus, so that the characteristic X-rays may also be accompanied by gamma rays from subsequent nuclear de-excitation.*

*Electron capture can lead to another form of continuous electromagnetic radiation known as inner bremsstrahlung. In the decay process, an orbital electron is captured by the nucleus and therefore must undergo some acceleration. From classical theory, an accelerated charge must emit electromagnetic radiation. Because the acceleration may vary over a wide range depending on the specifics of the capture process, the resulting emission spectrum is a continuum ranging up to a maximum photon energy given by the $Q$-value of the electron capture decay (the maximum energy available in the nuclear transition). Inner bremsstrahlung therefore adds a continuous electromagnetic spectrum to the other radiations normally expected as a product of the electron capture decay, although in many cases the intensity of this spectrum may be negligibly small.
Internal conversion is another nuclear process that can lead to characteristic X-rays. As defined earlier in this chapter, internal conversion results in the ejection of an orbital electron from the atom leaving behind a vacancy. Again, it is the K-electrons which are most readily converted, and therefore the K-series characteristic X-rays are the most prominent. Because gamma ray de-excitation of the nuclear state is always a competing process to internal conversion, radioisotope sources of this type usually emit gamma rays in addition to the characteristic X-ray spectrum. The conversion electrons may also lead to a measurable bremsstrahlung continuum, particularly when their energy is high.

In Table 13-2, some examples are given of radioisotopes that involve either electron capture or internal conversion and are possible sources of characteristic X-rays. In all these examples, the yield of high-energy gamma rays from a nuclear transition is large compared with that of the characteristic X-rays. If a pure X-ray source free of gamma ray contamination is required, a radioisotope which decays by electron capture leading directly to the ground nuclear state of the daughter must be chosen. Table 1-3 gives some examples for the lower energy range. Of these, $^{55}\text{Fe}$ is most widely used because of its convenient half-life and high available specific activity. It is very nearly a pure source of manganese K-series X-rays at about 5.9 keV, and the inner bremsstrahlung associated with the electron capture process is very weak.

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Half-Life</th>
<th>Weighted $\text{K}_\alpha$ X-Ray Energy</th>
<th>Fluorescent Yield</th>
<th>Other Radiations</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{37}\text{Ar}$</td>
<td>35.1 days</td>
<td>2.957 keV</td>
<td>0.086</td>
<td>Some IB$^a$</td>
</tr>
<tr>
<td>$^{41}\text{Ca}$</td>
<td>$8 \times 10^4$ y</td>
<td>3.690</td>
<td>0.129</td>
<td>pure</td>
</tr>
<tr>
<td>$^{44}\text{Ti}$</td>
<td>48 y</td>
<td>4.508</td>
<td>0.174</td>
<td>$\gamma$ rays at 68 and 78 keV</td>
</tr>
<tr>
<td>$^{49}\text{V}$</td>
<td>330 days</td>
<td>4.949</td>
<td>0.200</td>
<td>IB</td>
</tr>
<tr>
<td>$^{55}\text{Fe}$</td>
<td>2.60 y</td>
<td>5.895</td>
<td>0.282</td>
<td>weak IB</td>
</tr>
</tbody>
</table>

Data from Amlauer and Tuohy$^{11}$

$^a$IB represents inner bremsstrahlung.

Self-absorption is a significant technical problem in the preparation of radioisotope X-ray sources. As the thickness of the radioisotope deposit is increased, the X-ray flux emerging from its surface approaches a limiting value because only those atoms near the surface can contribute photons that escape. The number of emitting atoms within a given distance of the deposit surface is maximized by increasing the specific activity of the radioisotope, and “carrier free” samples will exhibit the maximum attainable source intensity per unit area.
2. EXCITATION BY EXTERNAL RADIATION

The general scheme sketched in Fig. 1-8 may also be used to generate characteristic X-rays. Here an external source of radiation (X-rays, electrons, alpha particles, etc.) is caused to strike a target, creating excited or ionized atoms in the target through the processes detailed in Chapter 2. Because many excited atoms or ions in the target subsequently de-excite to the ground state through the emission of characteristic X-rays, the target can serve as a localized source of these X-rays.

The energy of the X-rays emitted depends on the choice of target material. Targets with low atomic number result in soft characteristic X-rays, and high-Z targets produce harder or higher energy X-rays. The incident radiation must have an energy larger than the maximum photon energy expected from the target, because the excited states leading to the corresponding atomic transition must be populated by the incident radiation.

As one example, the incident radiation may consist of X-rays generated in a conventional X-ray tube. These X-rays may then interact in the target through photoelectric absorption, and the subsequent de-excitation of the target ions creates their characteristic X-ray spectrum. In this case, the process is called X-ray fluorescence. Although the characteristic X-ray spectrum can be contaminated by scattered photons from the incident X-ray beam, this component can be kept below about 10 or 20 percent of the total photon yield with proper choice of target and geometry.

Another method of exciting the target is through the use of an external electron beam. For targets of low atomic number, accelerating potentials of only a few thousand volts are required so that relatively compact electron sources can be devised. In the case of electron excitation, the characteristic X-ray spectrum from the target will be contaminated by the continuous bremsstrahlung spectrum also generated by interactions of the incident electrons in the target. For thin targets, however, the bremsstrahlung photons are preferentially emitted in the forward direction, whereas the characteristic X-rays are emitted isotropically. Placing the exit window at a large angle (120-180°) with respect to the incident electron direction will therefore minimize the bremsstrahlung contamination.

The incident radiation in Fig. 1-8 can also consist of heavy charged particles. Again, the interactions of these particles in the target will give rise to the excited

---

FIGURE 1-8. General method for the generation of characteristic X-rays from a specific target element. The exciting radiation can be X-rays, electrons, alpha particles, or any other ionizing radiation.
atoms necessary for the emission of characteristic X-rays. For compact and portable sources, alpha particles emitted by radioisotope sources are the most convenient source of the incident particles. Of the various potential alpha emitters, the most useful are \(^{210}\text{Po}\) and \(^{244}\text{Cm}\) because of their convenient half-lives and relative freedom from contaminant electromagnetic radiation (see Table 1-4). Alpha particle excitation avoids the complication of bremsstrahlung associated with electron excitation, and is therefore capable of generating a relatively “clean” characteristic X-ray spectrum. A cross-sectional diagram of a typical source of this type is shown in Fig. 1-9. The X-ray yield into one steradian solid angle per mCi (37 MBq) of \(^{244}\text{Cm}\) ranges from \(1.7 \times 10^2\) photons/second for a beryllium target to about \(10^4\) photons/second for targets of higher \(Z\) (Ref. 11).

### Table 1-4. Alpha Particle Sources Useful for Excitation of Characteristic X-Rays

<table>
<thead>
<tr>
<th></th>
<th>(^{210}\text{Po})</th>
<th>(^{244}\text{Cm})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half-Life</td>
<td>138 days</td>
<td>17.6 y</td>
</tr>
<tr>
<td>Alpha emissions</td>
<td>5.305 MeV (100%)</td>
<td>5.81, 5.77 MeV</td>
</tr>
<tr>
<td>Gamma Rays</td>
<td>803 keV (.0011%)</td>
<td>43 keV (.02%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100 keV (.0015%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>150 keV (.0013%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>262 keV (1.4 x (10^{-4}%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td>590 keV (2.5 x (10^{-4}%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td>820 keV (7 x (10^{-5}%))</td>
</tr>
<tr>
<td>X-Rays</td>
<td>Pb characteristic</td>
<td>Pu characteristic</td>
</tr>
<tr>
<td></td>
<td>L &amp; M (trace)</td>
<td>L &amp; M</td>
</tr>
</tbody>
</table>

Data from Amlauer and Tuohy.\(^{11}\)