is used to produce bremssstrahlung X-rays from X-rays tubes (see Sect. 2.1). However, a combination of the β source with the target material also creates a source of bremsstrahlung radiation. These sources with a continuous spectrum of bremsstrahlung can increase the set of available sources for excitation of characteristic radiation. The shape of the energy spectrum depends on the spectrum of β particles emitted by a radioactive source. The maximum energy in the spectrum of bremsstrahlung radiation is determined by the maximum energy of β particles.

Properties Connected with the Production of the Source

The properties of the sources my be differentiated according to the type of manufacture, dimensions, shapes, type of coating, etc.The type of coating influences the shape of the spectrum. Thicker coating or coating of a material with a higher Z can absorb low energy radiation from the source.

2.3.2 Radioisotope Sources

Source selection for different elements is based on the energy of source radiation. The atoms can be excited by photons having energies higher than the binding energy of the electron on the determined shells (K, L etc.). To excite Kα line of, e.g., Sn, the energy of an excited radiation must be greater than the binding energy on the Sn K shell, i.e., 29.19 keV. On the other hand, the exciting energy should also not be too high. The cross section of the photoeffect decreases if the energy rises, and, proportionally the probability of exciting the characteristic radiation also decreases. Every source has a group of elements for which the source is best suited [51].

The photons from the source can interact in the sample by Coherent scattering and Compton scattering too. This scattered radiation can be absorbed in the detector, and it can raise the background in a part of the spectrum and complicate the measurement of low intensity line in this part of the spectrum. A similar problem can cause escape peaks in the spectrum [49]. All these circumstances have to be taken into account when choosing the source.

Radioisotope Gamma and X-Ray Sources

The widely employed gamma and X-ray sources are given in Table 2.1, showing also the preferred element ranges. ^{55}Fe is a very useful source for elements with a low proton number. Its energy spectrum is shown in Fig. 2.18. ^{238}Pu, ^{244}Cm, and ^{109}Cd sources are used for exciting elements with $Z = 20-42$. The energy spectrum of ^{238}Pu and ^{109}Cd are shown in Figs. 2.19 and 2.20, respectively. ^{109}Cd is a source which emits X-rays due to K capture. Figure 2.21 shows the decay scheme of ^{109}Cd. Higher energies of photons are emitted by ^{241}Am and ^{57}Co. The energy spectrum of ^{241}Am and its decay scheme are shown in Figs. 2.22 and 2.23, respectively.

Table 2.1. Radioisotope gamma and X-ray sources [48, 52, 56]

Source	Half-life	Type of decay	Particle energy	Gamma rays Energy (keV)	Gamma rays Yield (%)	Characteristic X-rays Assignment	Characteristic X-rays Energy (keV)	Characteristic X-rays Yield (%)	Typical elemental range K lines	Typical elemental range L lines
^{55}Fe	2.73 y	EC	–	–	–	Mn $K_{\alpha 2}$	5.89	8.5	Si–V	Zr–Ce
						Mn $K_{\alpha 1}$	5.90	16.9		
						Mn $K_{\beta 1}$	6.49	2.0		
						Mn $K_{\beta 3}$	6.49	1.01		
^{57}Co	271.8 d	EC	–	14.41	9.16	Fe $K_{\alpha 2}$	6.39	16.4	Yb–U	
				122.06	85.60	Fe $K_{\alpha 1}$	6.40	32.6		
				136.47	10.68	Fe $K_{\beta 3}$	7.06	2.0		
						Fe $K_{\beta 1}$	7.06	3.9		
^{109}Cd	462.6 d	EC	–	88.04	3.61	Ag $K_{\alpha 2}$	21.99	29.5	Cr–Mo	Tb–U
						Ag $K_{\alpha 1}$	22.16	55.7		
						Ag $K_{\beta 3}$	24.91	4.8		
						Ag $K_{\beta 1}$	24.94	9.2		
						Ag $K_{\beta 2}$	25.46	2.3		
^{125}I	59.41 d	EC	–	35.49	6.68	Te $K_{\alpha 2}$	27.20	40.6	As–Cd	Tb–U
						Te $K_{\alpha 1}$	27.47	75.7		
						Te $K_{\beta 3}$	30.94	6.8		
						Te $K_{\beta 1}$	31.00	13.2		
						Te $K_{\beta 2}$	31.70	3.8		
^{145}Sm	340 d	EC	–	61.25	12.00	Pm $K_{\alpha 2}$	38.17	39.9	Ga–Tb	
						Pm $K_{\alpha 1}$	38.73	72.4		
						Pm $K_{\beta 3}$	43.71	7.0		
						Pm $K_{\beta 1}$	43.83	13.6		
						Pm $K_{\beta 2}$	44.94	4.5		
^{155}Eu	4.76 y	β−	134.1 keV	45.30	1.33	Gd $L_{\alpha 1}$	6.06	3.0	Pd–Ra	
			146.8 keV	60.01	1.13	Gd $L_{\beta 1}$	6.71	2.1		
			165.6 keV	86.55	30.70	Gd $K_{\alpha 2}$	42.31	6.6		
			192.1 keV	105.31	21.20	Gd $K_{\alpha 1}$	43.00	11.9		
			252.1 keV			Gd $K_{\beta 3}$	48.55	1.2		
						Gd $K_{\beta 1}$	48.70	2.3		
^{153}Gd	240.4 d	EC	–	69.67	2.42	Eu $L_{\alpha 1}$	5.85	8.8	Ba–Fr	
				97.43	29.00	Eu $L_{\beta 1}$	6.46	5.6		
				103.18	21.11	Eu $L_{\beta 2}$	6.84	1.9		
						Eu $K_{\alpha 2}$	40.90	35.2		
						Eu $K_{\alpha 1}$	41.54	63.5		
						Eu $K_{\beta 3}$	46.91	6.3		
						Eu $K_{\beta 1}$	47.04	12.1		
						Eu $K_{\beta 2}$	48.25	4.0		
^{170}Tm	128.6 d	β−	883.3 keV	84.25	2.50	Yb $L_{\alpha 1}$	7.42	1.1	Pd–Hg	
			968.0 keV			Yb $L_{\beta 1}$	8.40	1.0		
						Yb $K_{\alpha 2}$	51.35	0.94		
						Yb $K_{\alpha 1}$	52.39	1.7		
						Yb $K_{\beta 3}$	59.16	0.18		
						Yb $K_{\beta 1}$	59.38	0.34		
						Yb $K_{\beta 2}$	60.96	0.12		

Table 2.1. *Continued*

Source	Half-life	Type of decay	Particle energy	Gamma rays Energy (keV)	Gamma rays Yield (%)	Characteristic X-rays Assignment	Characteristic X-rays Energy (keV)	Characteristic X-rays Yield (%)	Typical elemental range K lines	Typical elemental range L lines
^{238}Pu	87.7 y	α	5.456 MeV	—	—	U L_l	11.62	0.26	Ca–Sr	Sn–At
			5.499 MeV			U $L_{\alpha 2}$	13.44	0.42		
						U $L_{\alpha 1}$	13.62	3.8		
						U $L_{\beta 2}$	16.41	1.00		
						U $L_{\beta 5}$	17.07	0.21		
						U $L_{\beta 1}$	17.22	3.9		
						U $L_{\gamma 1}$	20.17	0.94		
						U $L_{\gamma 6}$	20.84	0.20		
^{241}Am	432.2 y	α	5.485 MeV	26.34	2.40	Np $L_{\alpha 2}$	13.76	1.1	Zn–Nd	W–U
			5.422 MeV	33.20	0.13	Np $L_{\alpha 1}$	13.95	9.6		
			5.388 MeV	59.54	35.90	Np $L_{\beta 2}$	16.82	2.5		
						Np $L_{\beta 1}$	17.75	5.7		
						Np $L_{\beta 3}$	17.99	1.4		
						Np $L_{\gamma 1}$	20.78	1.4		
^{244}Cm	18.10 y	α	5.762 MeV	—	—	Pu $L_{\alpha 1}$	14.28	3.1	Ti–Se	Ba–Bi
			5.804 MeV			Pu L_{η}	16.33	0.08		
						Pu $L_{\beta 6}$	16.50	0.06		
						Pu $L_{\beta 2}$	17.24	0.82		
						Pu $L_{\beta 5}$	17.95	0.18		
						Pu $L_{\beta 1}$	18.30	3.0		
						Pu $L_{\gamma 1}$	21.42	0.73		
						Pu $L_{\gamma 6}$	22.15	0.15		

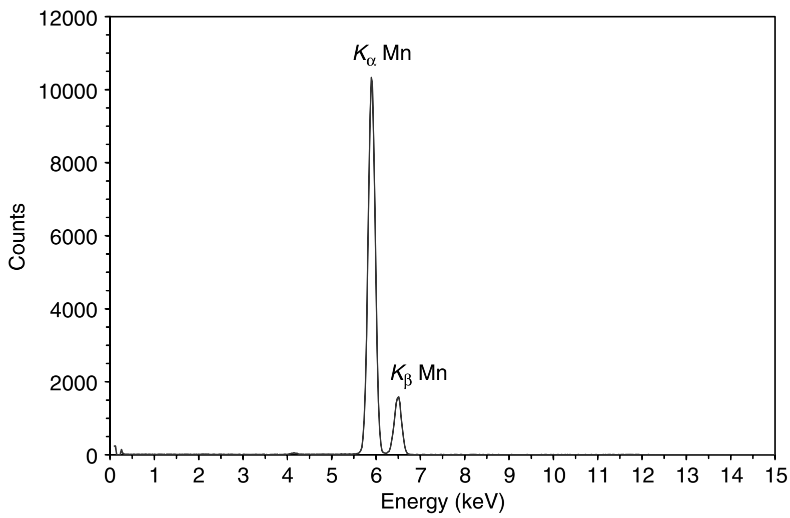

Fig. 2.18. X-ray spectrum from ^{55}Fe

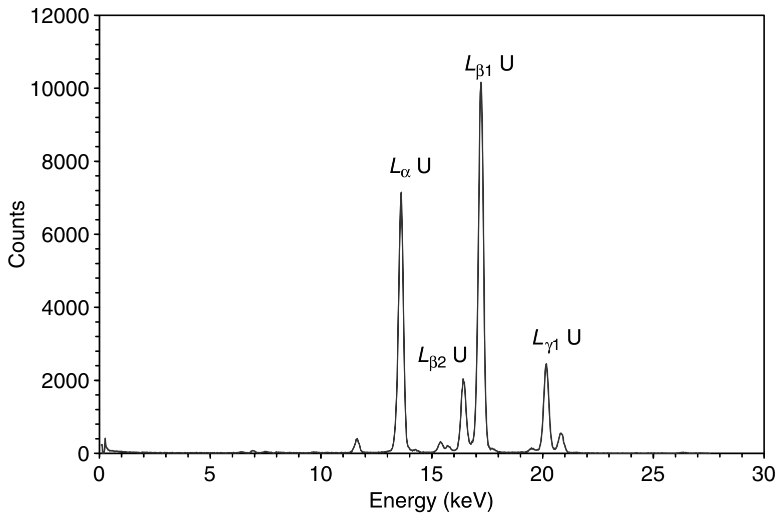

Fig. 2.19. X-ray spectrum from ^{238}Pu

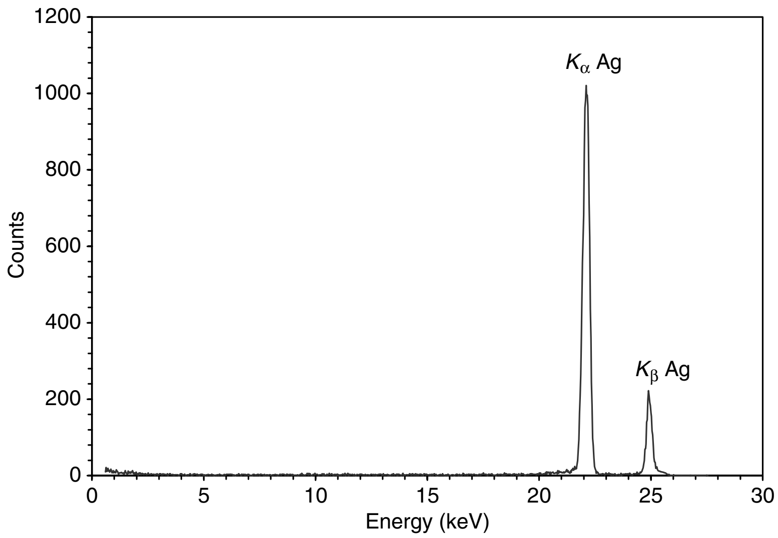

Fig. 2.20. X-ray spectrum from ^{109}Cd

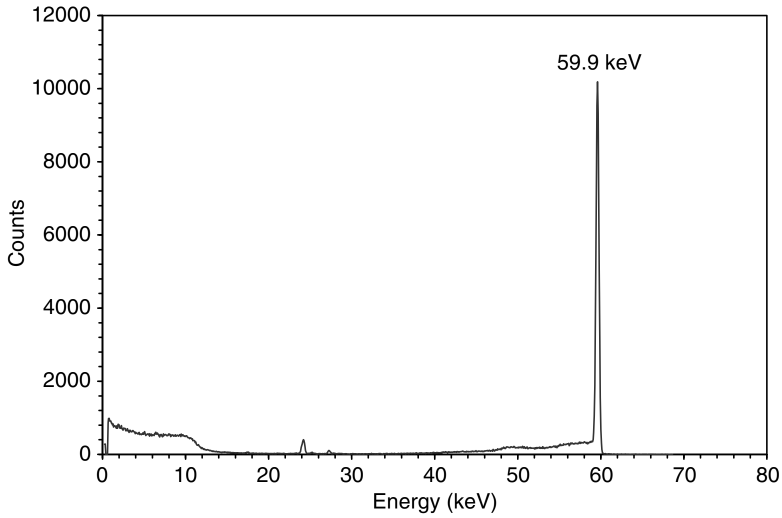

Fig. 2.21. X-ray and gamma ray spectrum from ^{241}Am

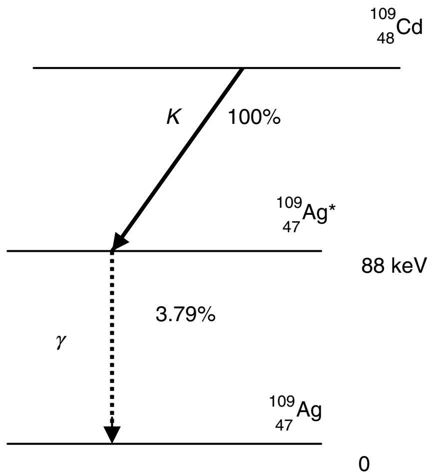

Fig. 2.22. Decay schema of the ^{109}Cd

Radioisotope Beta-excited X-Ray Sources

Beta excited X-ray sources complement the set of the sources available for XRA. The most important beta-excited X-ray sources are given in Table 2.2. They have a continuous spectrum in a wide range of energies. The bremsstrahlung radiation from the source is added to the characteristic radiation of the target material excited by beta particles or by the bremsstrahlung directly.

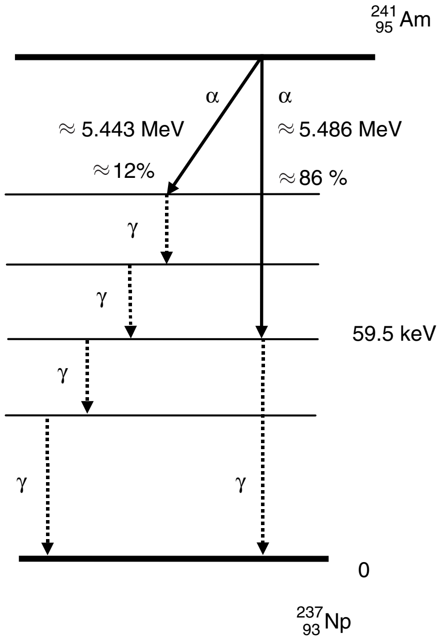

Fig. 2.23. Decay schema of the ^{214}Am

The relative high background of the scattered radiation in the measured spectrum is the disadvantage of beta-excited sources.The energy spectrum from ^{3}H/Zr is shown in Fig. 2.24.

Photon-Excited X-Ray Sources

The principle of photon-excited X-ray sources is based on the excitation of the target material by gamma radiation from the isotopic source. The advantage of these sources is that it is possible to choose the energy of the emitted radiation by selecting the target material. However, as compared with the

Table 2.2. Radioisotope beta-excited X-ray sources [48, 52]

Source	Half-life	Type of decay	Particle energy [keV]	Usable energetic range [keV]	Typical elemental range K line	Typical elemental range L lines
^{3}H/Ti	12.33 y	β−	18.59	4–8	Si-Cr	Ag-Sm
^{3}H/Zr	12.33 y	β−	18.59	5–9	Si-Zn	Ag-Tb
^{147}Pm/Al	2.62 y	β−	224.1	10–45	Mn-Nd	Tb-U

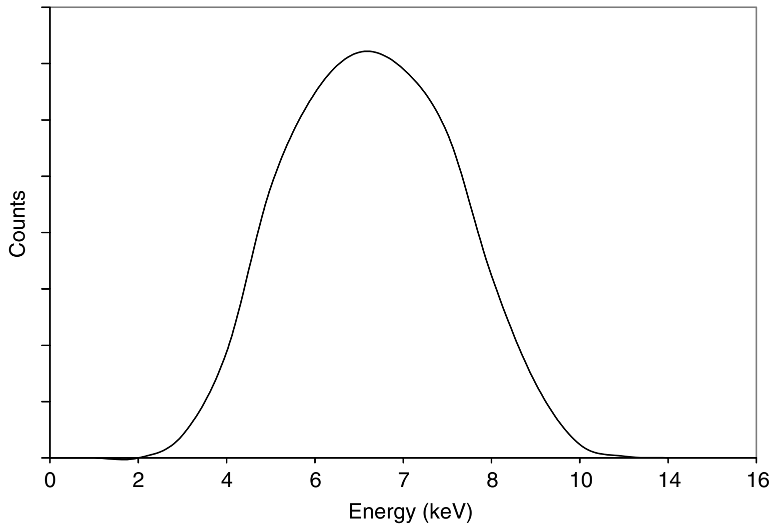

Fig. 2.24. Bremsstrahlung spectrum from $^{3}H/Zr$

primary photons, the main disadvantage is the low output of photons emitted from the target material. Using such sources makes it possible to replace the missing gamma and X-ray sources [53].

At present, photon excited X-ray sources are used for calibration purposes. The source can contain one radioactive source, e.g., ^{241}Am and several target materials. The source can emit characteristic radiation of elements in a wide range of energies. Figure 2.25 shows the spectra of Cu, Rb, Mo, Ag, Ba, and Tb emitted by such calibration variable energy source, presented in one diagram.

2.3.3 Production of Radioactive Sources

Radioisotope X-ray sources are produced by a number of manufacturers, e.g., [50, 54, 55, 58, 59]. For ^{55}Fe the radioactive material is electrodeposited as iron metal on a metal ring and sealed in a welded stainless steel capsule with a beryllium window. ^{238}Pu, ^{244}Cm, and ^{241}Am are incorporated in a ceramic enamel sealed in a stainless steal capsule with or without a Be window, etc. Figures 2.26 and 2.27 show a typical disk source and annular source used by XRF. The use of annular sources is typical of devices with detectors having a small window (e.g., semiconductor detectors). Mostly ring sources are used because of higher photon fluxes. A photo of an Amersham [57] ring source is given in Fig. 2.28.

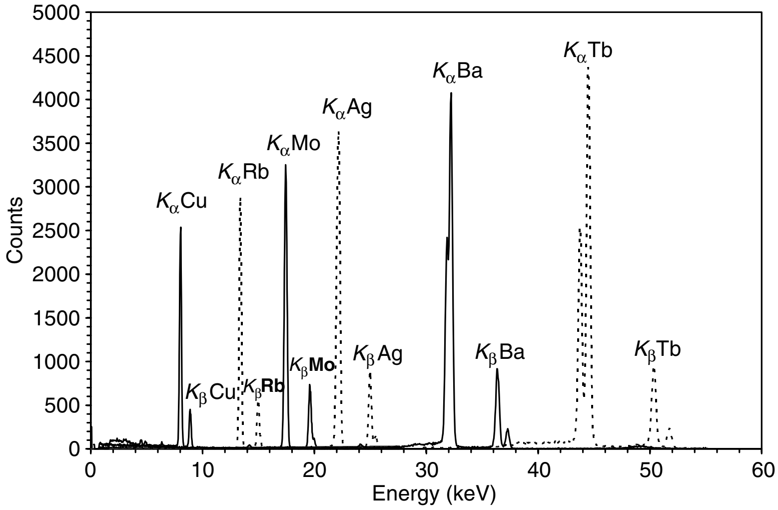

Fig. 2.25. X-ray spectra from calibration variable energy source 3837LA Amersham

2.3.4 Radiation Protection Regulations

The use of radioactive radiation sources in XRF equipment is approved and controlled by the appropriate National Radiation Safety Agency. The basic principle is that any person working with this type of equipment should not receive a dose of more than 1 millisievert yearly. The radioactive sources are generally required to be inspected every two years by independent experts in order to control the tightness of the seals.

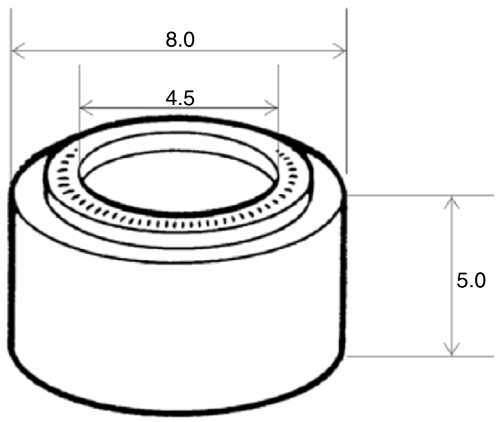

Fig. 2.26. Example of a typical disc source

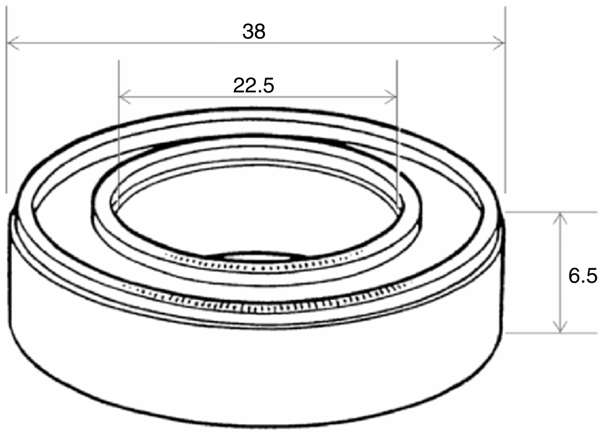

Fig. 2.27. Example of a typical annular source

Fig. 2.28. The photo of a ^{241}Am-ringshaped XRF-source [12]