## Table 4
## PARAMETERS OF MÖSSBAUER RESONANCE

| A | Element | E (keV) | $I_g$ | $I_e$ | $\alpha_T$ | BR (%) | a (%) |
|---|---|---|---|---|---|---|---|
| 57 | Fe | 14.41 | 1/2 | 3/2 | 8.20 | 100 | 2.14 |
| 61 | Ni | 67.40 | 3/2 | 5/2 | 0.135 | 100 | 1.19 |
| 67 | Zn | 93.32 | 5/2 | 1/2 | 0.89 | 100 | 4.11 |
| 99 | Ru | 89.36 | 5/2 | 3/2 | 1.54 | 100 | 12.72 |
| 119 | Sn | 23.87 | 1/2 | 3/2 | 5.12 | 100 | 8.58 |
| 121 | Sb | 37.15 | 5/2 | 7/2 | 10.60 | 100 | 57.25 |
| 125 | Te | 35.46 | 1/2 | 3/2 | 13.65 | 100 | 6.99 |
| 127 | I | 57.60 | 5/2 | 7/2 | 3.78 | 100 | 100 |
| 129 | I | 27.77 | 7/2 | 5/2 | 5.10 | 100 | $0^{a,b}$ |
| 129 | Xe | 39.58 | 1/2 | 3/2 | 12.30 | 100 | 26.44 |
| 133 | Cs | 80.99 | 7/2 | 5/2 | 1.7 | 100 | 100 |
| 141 | Pr | 145.43 | 5/2 | 7/2 | 0.46 | 100 | 100 |
| 145 | Nd | 72.50 | 7/2 | 5/2 | 4.90 | 100 | 8.29 |
| 149 | Sm | 22.49 | 7/2 | 5/2 | 50. | 100 | 13.83 |
| 151 | Eu | 21.53 | 5/2 | 7/2 | 28.60 | 100 | 47.82 |
| 153 | Eu | 103.18 | 5/2 | 3/2 | 1.78 | 99.40 | 52.18 |
| 155 | Gd | 86.54 | 3/2 | 5/2 | 0.43 | 96 | 14.73 |
| 161 | Dy | 25.65 | 5/2 | 5/2 | 2.90 | 100 | 18.88 |
| 166 | Er | 80.56 | 0 | 2 | 6.93 | 100 | 33.41 |
| 169 | Tm | 8.42 | 1/2 | 3/2 | 268. | 100 | 100 |
| 170 | Yb | 84.25 | 0 | 2 | 6.20 | 100 | 3.03 |
| 171 | Yb | 66.72 | 1/2 | 3/2 | 13. | 100 | 14.31 |
| 178 | Hf | 93.17 | 0 | 2 | 4.60 | 100 | 27.14 |
| 181 | Ta | 6.24 | 7/2 | 9/2 | 46. | 100 | 99.98 |
| 182 | W | 100.1 | 0 | 2 | 3.90 | 100 | 26.41 |
| 189 | Os | 36.22 | 3/2 | 1/2 | 80. | 100 | 16.10 |
| 189 | Os | 69.6 | 3/2 | 5/2 | 8. | 100 | 16.10 |
| 193 | Ir | 73.04 | 3/2 | 1/2 | 6.50 | 100 | 62.70 |
| 195 | Pt | 98.85 | 1/2 | 3/2 | 7.20 | 100 | 33.80 |
| 197 | Au | 77.35 | 3/2 | 1/2 | 4.30 | 100 | 100 |
| 237 | Np | 59.54 | 5/2 | 5/2 | 1.12 | 94 | $0^{a,c}$ |

[a] Radioactive isotope which has no natural abundance, but can be produced artificially in sufficient quantities. A value of a = 100% is used in the calculations.

[b] $t_{1/2} = 1.57 \times 10^7$ years.

[c] $t_{1/2} = 2.14 \times 10^6$ years.

# VI. MÖSSBAUER SPECTROSCOPY SOURCE MATERIALS AND THEIR PROPERTIES

**Z. M. Stadnik**

A good Mössbauer source should emit a monochromatic line with a width which is very close to natural Heisenberg width $\Gamma_{nat}$ and should have a substantial fraction of zero-phonons $f_s$. Source materials selected for inclusion in Table 6 are those for which these two parameters are the best currently known. For these materials values of $f_s$ are compiled from the literature. Some of the values have been calculated using standard statistical procedures, the details of which are described elsewhere.[5] Uncertainties of $f_s$, given in parentheses, indicate calculated standard deviation; e.g., 0.784(9) = 0.784 ± 0.009. For some source materials there are no experimental data on $f_s$ available. For these materials only the suitable source temperature $T_s$ is given.

## Table 5
## CALCULATED VALUES OF ABSORBER THICKNESS $d_2$ IN MG/CM$^2$ OF THE NATURAL ISOTOPIC ADMIXTURE

| Isotope (Energy) | $d_2(\theta_D = 100\ K)$ | | | $d_2(\theta_D = 150\ K)$ | | | $d_2(\theta_D = 200\ K)$ | | | $d_2(\theta_D = 250\ K)$ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 300 K | 77 K | 4.2 K | 300 K | 77 K | 4.2 K | 300 K | 77 K | 4.2 K | 300 K | 77 K | 4.2 K |
| $^{57}$Fe (14.4) | 261 | 11 | 5 | 24 | 5.9 | 4.4 | 10.3 | 4.8 | 4.1 | 7 | 4.3 | 4 |
| $^{61}$Ni (67.4) | | | 40268 | | | 3281 | | 18483 | 951 | | 2341 | 454 |
| $^{67}$Zn (93.3) | | | | | | 586890 | | | 67592 | | 325640 | 18590 |
| $^{99}$Ru (89.4) | | | | | | 6635 | | | 1735 | | 4604 | 776 |
| $^{119}$Sn (23.8) | 965 | 15 | 5.3 | 41 | 6.7 | 4.5 | 14 | 5 | 4.2 | 8.3 | 4.4 | 4 |
| $^{121}$Sb (37.1) | | 129 | 11 | 1447 | 19 | 7.3 | 105 | 9.5 | 6.1 | 31 | 7 | 5.4 |
| $^{125}$Te (35.5) | | 546 | 61 | | 100 | 43 | 455 | 55 | 37 | 156 | 41 | 33 |
| $^{127}$I (57.6) | | | 28 | | 100 | 11 | | 21 | 7.5 | 317 | 10 | 5.8 |
| $^{129}$I (27.8) | | 7.3 | 2 | 26 | 2.7 | 1.6 | 6.6 | 1.9 | 1.5 | 3.5 | 1.6 | 1.4 |
| $^{129}$Xe (39.6) | | 327 | 23 | | 42 | 15 | 262 | 20 | 12 | 72 | 15 | 11 |
| $^{133}$Cs (80.9) | | | 575 | | | 110 | | 343 | 48 | | 87 | 30 |
| $^{141}$Pr (145.4) | | | | | | | | | 7380 | | | 1665 |
| $^{145}$Nd (72.5) | | | 3652 | | | 1078 | | 2500 | 590 | | 914 | 411 |
| $^{149}$Sm (22.5) | 2834 | 148 | 71 | 304 | 83 | 63 | 139 | 68 | 60 | 97 | 62 | 58 |
| $^{151}$Eu (21.5) | 169 | 12 | 6 | 22 | 7 | 5.4 | 11 | 5.8 | 5.1 | 8 | 5.3 | 5 |
| $^{153}$Eu (103) | | | | | | 1765 | | 8878 | 555 | | 1288 | 278 |
| $^{155}$Gd (86.5) | | | 1317 | | | 259 | | 795 | 116 | | 208 | 72 |
| $^{161}$Dy (25.6) | 380• | 11• | 4.5• | 26• | 5.5• | 3.9• | 10• | 4.3• | 3.6• | 6.5• | 3.8• | 3.5• |
| $^{166}$Er (80.6) | | | 343 | | 2325 | 92 | | 228 | 48 | | 77 | 33 |
| $^{169}$Tm (8.4) | 3.6 | 2.5 | 2.3 | 2.7 | 2.3 | 2.3 | 2.5 | 2.3 | 2.2 | 2.4 | 2.2 | 2.2 |
| $^{170}$Yb (84.2) | | | 5014 | | | 1230 | | 3240 | 614 | | 1017 | 406 |
| $^{171}$Yb (66.7) | | | 679 | | 2427 | 283 | | 517 | 183 | | 251 | 141 |
| $^{178}$Hf (93.2) | | | 1122 | | | 217 | | 674 | 97 | | 174 | 60 |
| $^{181}$Ta (6.2) | 0.5• | 0.4• | 0.4• | 0.4• | 0.4• | 0.4• | 0.4• | 0.4• | 0.4• | 0.4• | 0.4• | 0.4• |
| $^{182}$W (100.1) | | | 2230 | | | 349 | | 1254 | 140 | | 272 | 81 |
| $^{189}$Os (36.2) | | 3074 | 677 | | 951 | 536 | 2708 | 630 | 477 | 1293 | 520 | 446 |
| $^{189}$Os (69.6) | | | 597 | | 2092 | 252 | | 456 | 165 | | 224 | 128 |
| $^{193}$Ir (73) | | | 527 | | 2040 | 208 | | 395 | 131 | | 183 | 100 |
| $^{195}$Pt (98.8) | | | 4650 | | | 861 | | 2754 | 374 | | 686 | 227 |
| $^{197}$Au (77.3) | | | 351 | | 1552 | 126 | | 255 | 76 | | 110 | 56 |
| $^{237}$Np (59.5) | | 298• | 11.4• | 7084• | 24• | 6.9• | 227• | 9.8• | 5.4• | 46• | 6.5• | 4.6• |

• Should be multiplied by a factor of 10 because of line broadening.

## Table 6
## SOURCE MATERIALS AND THEIR PROPERTIES

| Isotope | Eγ (keV) | $W_s$ (mm/sec) | Source Material | $T_s$(K) | $f_s$ |
|---|---|---|---|---|---|
| $^{57}$Fe[a] | 14.41 | 0.194 | Cr | 300 | 0.784(9) |
| | | | SS310 | 300 | 0.604(47) |
| | | | SS | 300 | 0.678(20) |
| | | | Rh | 300 | 0.784(13) |
| | | | | 4.2 | 0.875(18) |
| | | | Pd | 300 | 0.660(1) |
| | | | | 77 | 0.863(2) |
| | | | | 4.2 | 0.813(17) |
| | | | Cu | 300 | 0.708(1) |
| | | | | 4.2 | 0.910(2) |
| | | | | 4.2 | 0.851(53) |
| | | | CoO | 300 | 0.735(27) |
| | | | | 77 | 0.890(4) |
| $^{61}$Ni[b] | 67.41 | 0.770 | Ni-Cr alloy | 4.2 | |
| | | | Ni-V alloy | 4.2 | 0.162(3) |
| $^{99}$Ru[c] | 89.36 | 0.149 | Ru(Rh) | 4.2 | 0.140(50) |
| $^{119}$Sn[d] | 23.87 | 0.646 | $SnO_2$ | 300 | 0.471(28) |
| | | | | 77 | 0.585(35) |
| | | | | 4.2 | 0.885(15) |
| | | | $CaSnO_3$ | 300 | 0.574(17) |
| | | | $BaSnO_3$ | 300 | 0.623(21) |
| | | | Pd(Sn) | 300 | 0.383(29) |
| | | | $Pd_3Sn$ | 300 | 0.340(50) |
| | | | | 4.2 | 0.750(15) |
| | | | V(Sn) | 300 | 0.460(30) |
| | | | | 77 | 0.780(30) |
| | | | $Mg_2Sn$ | 300 | 0.280(26) |
| | | | | 77 | 0.770(80) |
| $^{119}$Sn[d] | 23.87 | 0.646 | α-Sn | 77 | |
| | | | β-Sn | 300 | 0.046(3) |
| | | | | 77 | 0.446(12) |
| | | | | 4.2 | 0.716(16) |
| $^{121}$Sb[e] | 37.15 | 2.10 | $SnO_2$ | 300 | 0.212(21) |
| | | | | 77 | 0.320(31) |
| | | | $BaSnO_3$ | 77 | 0.450(50) |
| | | | β-Sn | 77 | 0.160(20) |
| | | | $Ni_{21}Sn_2B_6$ | 300 | 0.070(20) |
| | | | | 77 | 0.290(50) |
| $^{125}$Te[f] | 35.46 | 5.209 | β-$TeO_3$ | 300 | 0.320(40) |
| | | | | 77 | 0.531(23) |
| | | | PbTe | 300 | <0.029 |
| | | | | 77 | 0.250(32) |
| | | | Cu(1) | 77 | 0.143(30) |
| | | | | 4.2 | 0.400(50) |
| | | | Rh(Sb) | 4.2—77 | |
| | | | Cu(Sb) | 300 | <0.029 |
| | | | | 77 | 0.442(59) |
| $^{127}$I[g] | 57.60 | 2.49 | ZnTe | 4.2 | 0.120(24) |
| $^{129}$I[h] | 27.77 | 0.586 | ZnTe | 77 | 0.232(43) |
| $^{149}$Sm[i] | 22.49 | 1.708 | $Eu_2O_3$ | 300 | |
| | | | $EuF_3$ | 300 | |
| $^{151}$Eu[j] | 21.53 | 1.31 | $SmF_3$ | 300 | 0.275(125) |
| | | | $SmF_3 \cdot 2H_2O$ | 300 | |
| | | | $Sm_2O_3$ | 300 | 0.440(60) |
| $^{153}$Eu[k] | 103.2 | 0.68 | $Sm_2O_3$ | 20 | 0.050(10) |

## Table 6 (continued)
## SOURCE MATERIALS AND THEIR PROPERTIES

| Isotope | $E_\gamma$ (keV) | $W_0$ (mm/sec) | Source Material | $T_s$(K) | $f_s$ |
|---|---|---|---|---|---|
| $^{155}$Gd[l] | 86.55 | 0.499 | Pd(Eu) | 4.2 | 0.110(10) |
| | | | Sm(Eu) | 4.2 | |
| | | | $Sm_2Sn_2O_7$ | 4.2 | |
| $^{161}$Dy[m] | 26.66 | 0.378 | $Gd_2O_3$ | 300 | 0.230(50) |
| | | | $GdF_3$ | 300 | |
| | | | Gd(Tb) | 300 | |
| $^{166}$Er[n] | 80.56 | 1.816 | $HoAl_2$ | 25—30 | |
| $^{170}$Yb[o] | 84.25 | 2.019 | $TmB_{12}$ | 4.2 | 0.340(10) |
| | | | $TmAl_2$ | 4.2 | 0.180(10) |
| | | | Tm | 4.2 | |
| $^{181}$Ta[p] | 6.24 | 0.0064 | Mo(W) | 300 | |
| | | | W | 300 | |
| | | | Ta(W) | 300 | |
| | | | Pt(W) | 300 | |
| $^{182}$W[q] | 100.1 | 2.09 | Ta | 4.2 | 0.150(30) |
| $^{193}$Ir[r] | 73.04 | 0.595 | Pt(Os) | 4.2 | |
| | | | Os | 4.2 | |
| | | | Nb(Os) | 4.2 | |
| | | | V(Os) | 4.2 | |
| $^{195}$Pt[s] | 98.86 | 16.28 | Pt(Au) | 20 | 0.089(2) |
| | | | | 77 | 0.021(3) |
| | | | Pt | 4.2 | |
| | | | Ir (Au) | 20 | 0.0523(5) |
| $^{197}$Au[t] | 77.35 | 1.882 | Pt | 77 | 0.069(5) |
| | | | | 4.2 | 0.272(26) |
| $^{237}$Np[u] | 59.54 | 0.067 | Th(Am) | 4.2—77 | |
| | | | $VO_2$ | 4.2—77 | |

*Note:* Much useful information on the methodology of many Mössbauer isotopes can be found in Reference 40. This survey covers the literature through June, 1977. More detailed data and information on any isotope may be obtained from the author. Both the author and the staff at the Mössbauer Effect Data Center would appreciate receiving additional information, published or unpublished, which will add to or modify the material presented above.

[a] The 14.41 keV level is populated by election capture decay of $^{57}$Co (which is the most frequent route of population), by Coulomb excitation, and by nuclear reaction. The parent nucleus $^{57}$Co is produced by irradiating an iron target with 9.5-MeV deuterons (for this energy this process is the most efficient) by the reaction $^{56}$Fe(d,n) $^{57}$Co. After irradiation the target is dissolved in mineral acids. The radioactive carrier free $^{57}$Co is obtained by isopropyl ether extraction, which is followed by an ion exchange separation. Next, the carrier free $^{57}$Co is deposited on the surface of a suitable matrix by means of the electrolytic method or by evaporation to dryness of $^{57}$Co salt solution. Then $^{57}$Co is diffused into the matrix by annealing at an appropriately high temperature in vacuum or in inert gas atmosphere during a suitable period of time.

At the initial stage of development of Mössbauer spectroscopy the commonly used source was $^{57}$Co in stainless steel because of its easy preparation. However, it emitted a considerably broadened line due to the existence of various impurities and large resonance self-absorption in stainless steel. The best single line sources are $^{57}$Co in Pt, Pd, Cu, and Cr matrices, of which $^{57}$Co in Cr has the largest $f_s$ and $^{57}$Co in Pd the smallest. The intermediate values of $f_s$, approximately equal, are characteristic for $^{57}$Co in Pt, and Cu matrices. The linewidths of the sources $^{57}$Co in Cu, Pt, and Pd are very close to the natural linewidth. The $^{57}$Co in Cr source emits a slightly broadened line, but if suitable source preparation procedure is employed this source also gives an unbroadened line.[6] The disadvantage of $^{57}$Co in Pt, $^{57}$Co in Pd sources is comparatively large atomic absorption (large Z). There are some difficulties in producing thin Cr foils for the $^{57}$Co in Cr source and the use of thick foils requires very precise homogeneous distribution of $^{57}$Co in the surface layer. The $^{57}$Co in Cu source is not chemically stable; Cu has very low solubility for Fe and Co, and it gives an anomalously asymmetric line. This asymmetry may be removed by appropriate source preparation.[7] The source in the form of $^{57}$Co in CoO has also very good parameters.[8] $^{57}$Co in Cr seems to be the best source at 300 K and $^{57}$Co in Rh at 4.2 K.

## Table 6 (continued)
## SOURCE MATERIALS AND THEIR PROPERTIES

In certain experiments such as investigation of the Mössbauer effect in scattering geometry or under high pressures, strong sources are needed. The increase in source activity deteriorates the source parameters on account of considerable broadening of the emission line caused by resonance self-absorption. This resonance broadening seems to be the limiting factor for strong sources. $^{57}$Co in stainless steel is better as a strong source than $^{57}$Co in Cu and Pd. It was found that non-ferromagnetic compounds of high Co content may be used as high-activity sources.[9] They have high $f_s$ and emit single broadened lines. CoO is also a good matrix for a high-activity source.

Mössbauer experiments using polarized gamma radiation give significant simplification of complex spectra and yield a considerable amount of information, not, or with difficulty, obtainable by means of unpolarized radiation. The difficulty lies in producing a source emitting a single line of definite polarization. The simplest polarized source is $^{57}$Co in an iron foil magnetized in the proper direction, but the emission line is not monochromatic and the absorption spectra are complex. A better polarized source, although emitting two lines, is $^{57}$Co embedded into a suitable monocrystal. A single line source of definite polarization may be obtained using a suitable moving filter (this requires two driving systems) or a motionless properly prepared filter.[6-11]

[b] The radioactive decay of $^{61}$Co, produced by $^{64}$Ni(p,$\alpha$)$^{61}$Co , $^{62}$Ni($\gamma$, p) $^{61}$Co reactions, and $^{61}$Cu, produced by $^{63}$Cu($\gamma$,2n) $^{61}$Cu, $^{60}$Ni(d,n) $^{61}$Cu, $^{58}$Ni($\alpha$,n) $^{61}$Zn electron capture $^{61}$Cu reactions, both populate the 67.41 keV level of $^{61}$Ni. The $^{61}$Cu parent nucleus has not been utilized as often as $^{61}$Co because of the complexity of the decay scheme and the difficulty in its production. The emission line of the sources using Ni matrix is broadened owing to magnetic hyperfine interactions. The cubic matrices prepared by alloying either chromium or vanadium with Ni (about 15% Cr or V) proved to be very useful because the Curie point of nickel decreases rapidly with the addition of these elements. At 4.2 K $^{61}$Co in these matrices gives a single line very close in width to $\Gamma_{nat}$.[12]

[c] The parent nucleus $^{99}$Rh may be produced by $^{99}$Ru(p,n) $^{99}$Rh or by $^{99}$Ru(d,2n) $^{99}$Rh reaction. A ruthenium metal host lattice, even though it has a hexagonal structure, was used in all reported studies. The $^{99}$Rh in Ru source gives a single line. A slight broadening is caused by quadrupole interaction and resonance self-absorption in the Ru matrix. The source produced by Ru bombardment without further chemical treatment shows an appreciably smaller $f_s$ than that produced by chemical separation of $^{99}$Rh activity followed by re-incorporation into Ru metal. Cubic Rh may be used as a source material but it has a much lower $f_s$.[13]

[d] The 23.87 keV level is populated by isomeric transition in $^{119m}$Sn, produced through $^{118}$Sn(n,$\gamma$) $^{119m}$Sn reaction, or by electron capture decay of $^{119}$Sb produced by $^{119}$Sn(p,n) $^{119}$Sn(p,n) $^{119}$Sb or $^{120}$Sn(p,2n) $^{119}$Sb reaction. In nearly all sources isomeric transition in $^{119m}$Sn is employed. The sources used in early measurements were $^{119m}$Sn in $SnO_2$ and Sn. The $^{119m}$Sn in $SnO_2$ source has a high $f_s$ at 300 K but there are some problems in precise definition of its stoichiometry and the width of its emission line is more than two times greater than $\Gamma_{nat}$. The main disadvantage of $^{119m}$Sn in $\alpha$-Sn and $\beta$-Sn sources, apart from line broadening, is a very low $f_s$ at 300 K. The $^{119m}$Sn in $Mg_2Sn$ source gives a slightly broadened line but it has a rather small $f_s$ at 300 K, hence either cooling of the source or long-data accumulation time is required. Furthermore, $Mg_2Sn$ is chemically unstable when exposed to moisture, resulting in an increase in emission linewidth. A very good source, now frequently used, is $^{119m}$Sn in $BaSnO_3$. It emits a single line very close in width to $\Gamma_{nat}$ and has a high $f_s$ at 300 K. The Pd(Sn) source material also has good parameters at 300 K. However, apart from the $Pd_{0.97}Sn_{0.03}$ matrix, there may exist different $Pd_xSn_y$ compounds, since $Pd_xSn_y$ is a substitutional type alloy, resulting in broadened of the emission line. Good sources, though less often used, are $^{119m}$Sn in $Pd_3Sn$ and $CaSnO_3$.[14-18]

[e] The 37.15 keV level is entirely populated by $\beta^-$-decay of $^{121m}$Sn produced by $^{120}$Sn(n,$\gamma$)$^{121m}$Sn reaction. The first source used was $^{121m}$Sn in $\beta$-Sn, but it had a small value of $f_s$ and gave a slightly broadened line owing to the non-cubic $\beta$-Sn matrix. The sources mainly employed now are $^{121m}$Sn in $SnO_2$, $BaSnO_3$, $CaSnO_3$ and $Ni_{21}Sn_2B_6$ matrices. All these sources emit slightly broadened single lines. The stannate sources are probably preferable to $^{121m}$Sn in $SnO_2$ sources because of the higher $f_s$ of the former and the non-cubic symmetry of the latter. All the above-mentioned sources, except $^{121m}$Sn in $Ni_{21}Sn_2B_6$, show very large isomer shifts relative to InSb, which means that a large velocity scale is required for the investigation of Sb compounds. The $^{121m}$Sn in $Ni_{21}Sn_2B_6$ source does not have this disadvantage. Its parameters are comparable with the other sources at 77 K.[19]

[f] The 35.46 keV level of $^{125}$Te may be populated by $\beta$ -decay of $^{125}$Sb, produced via $^{124}$Sn(n,$\gamma$) $^{125m}$Sn$\rightarrow$ / $\beta$-decay $^{125}$I reaction, or isomeric transition in $^{125m}$Te, produced through $^{124}$Te(n,$\gamma$) $^{125m}$Te reaction. The source with the highest $f_s$ is $^{125m}$Te in $\beta$-$TeO_3$. Its only disadvantage is a short half-life (fifty-eight days)

## Table 6 (continued)
## SOURCE MATERIALS AND THEIR PROPERTIES

of the metastable $^{125m}$Te state. The sources in which the parent nucleus is $^{125}$Sb ($t_{1/2}$ = 2.7 years) do not have this drawback. From them $^{125}$Sb in Rh has been found to be the best. The sources using $^{125}$I parent nucleus have substantially worse parameters.[20,21]

[g] The parent nucleus $^{127m}$Te is produced via $^{126}$Te(n,γ) $^{127m}$Te reaction. The commonly used source is $^{127m}$Te in ZnTe which emits a single line very close in width to $\Gamma_{nat}$. The Te(OH)$_6$ and Te matrices have been less satisfactorily used.[22,23]

[h] The parent nuclei $^{129m}$Te and $^{129}$Te of $^{129}$I Mössbauer isotope are obtained by $^{128}$Te(n,γ) reaction. The matrix generally used is ZnTe. The value of $f_s$ for the $^{129m}$Te in ZnTe source is about four times smaller than for the $^{129}$Te in ZnTe source and hence tended to be preferred in Mössbauer spectroscopy of the latter. However, the short half-life restricts its applicability to laboratories not too far from a reactor.[24]

[i] The parent nucleus $^{149}$Eu is obtained by $^{150}$Sm(p,2n) $^{149}$Eu or $^{149}$Sm(p,n) $^{149}$Eu reaction, or by a spallation by irradiation of Ta with protons. The irradiated Sm$_2$O$_3$ may be directly used as the source or $^{149}$Eu activity may be separated by ion-exchange techniques and incorporated into Eu$_2$O$_3$. There is no resonance self-absorption in the latter source. A good source is $^{149}$Eu in EuF$_3$. It emits a slightly broadened line due to unresolved quadrupole interaction and paramagnetic hyperfine effects. All sources are used at room temperature since lower temperatures produce substantial line broadening owing to paramagnetic hyperfine effects.[25]

[j] This Mössbauer level may be populated by electron capture decay of $^{151}$Gd, produced by $^{151}$Eu(p,n) $^{151}$Gd or $^{151}$Eu(d,2n) $^{151}$Gd reaction, β -decay of $^{151}$Sm, produced by $^{150}$Sm(n,γ) $^{151}$Sm reaction, and by Coulomb excitation. $^{151}$Gd in Nd$_2$O$_3$ and in Eu$_2$O$_3$ and $^{151}$Sm in Sm$_2$O$_3$ and in SmF$_3$ give a single line without appreciable hyperfine broadening and have a high $f_s$ at 300 K. In a Coulomb excitation experiment the Eu$_2$O$_3$ target emits a single, slightly broadened line.[26]

[k] The 103.2 keV level is populated by electron capture decay of $^{153}$Gd, produced by $^{152}$Gd(n, γ) $^{153}$Gd, $^{153}$Eu(d,2n) $^{153}$Gd, $^{153}$Eu(p,n) $^{153}$Gd reactions, or by β -decay of $^{153}$Sm, produced by $^{152}$Sm(n,γ) $^{153}$Sm reaction. A widely-used source is $^{153}$Sm in Sm$_2$O$_3$. It emits a single line width of about 2$\Gamma_{nat}$. The $^{153}$Sm in SmPd$_3$ source gives a narrower emission line.[27,28]

[l] The parent nucleus $^{155}$Eu is produced via $^{154}$Sm(n,γ) $^{155}$Sm β -decay $^{155}$Eu reaction. The sources initially used, $^{155}$Eu in Sm$_2$O$_3$ and in SmH$_2$, give split emission lines. The sources in YbAl$_2$ and Sm$_{0.05}$Al$_{0.95}$ matrices suffer from line broadening. Good parameters are characteristic for the sources of $^{155}$Eu in Sm$_2$Sn$_2$O$_7$, Pd, SmPd$_3$.[29,30]

[m] The parent nucleus $^{161}$Tb is produced by $^{160}$Gd(n,γ) $^{161}$Gd β -decay $^{161}$Tb reaction. The sources $^{161}$Tb in Gd$_2$O$_3$ and in Dy$_2$O$_3$ used initially emit single, very broad lines. Their linewidths are two orders of magnitude greater than $\Gamma_{nat}$. The $^{161}$Tb in Mg and $^{161}$Tb in Mo sources emit slightly narrower lines. This broadening is caused by paramagnetic relaxation effects. The $^{161}$Tb in Gd$_{0.5}$Dy$_{0.5}$F$_3$ and $^{161}$Tb in GdF$_3$ sources are much better than those mentioned above. The sharpest line is emitted from the $^{161}$Tb in Gd$_2$Ti$_2$O$_7$ source but its temperature must be kept at 150K.[31,32]

[n] The parent nucleus $^{166}$Ho is obtained via the reaction $^{165}$Ho(n,γ) $^{166}$Ho. The source $^{166}$Ho in Ho$_2$O$_3$ used at the beginning gives a very broad line. A better source, widely used now, is $^{166}$Ho in HoAl$_2$, whose linewidth is about three times greater than $\Gamma_{nat}$, but which must be kept at 25-30 K in order to avoid magnetic hyperfine splittings. The $^{166}$Ho in Ho$_{0.15}$Y$_{0.85}$Al$_2$ source also gives an unsplit line but it may be kept at lower temperatures than the Curie point (27 K) of the HoAl$_2$ matrix. The single line source $^{166}$Ho in (Ho$_{0.4}$Y$_{0.6}$)H$_2$ matrix may be used at 4.2 K, and its preparation is easy.[33]

[o] The parent nucleus $^{170}$Tm is produced by $^{169}$Tm(n,γ) $^{170}$Tm reaction. The sources generally used are $^{170}$Tm in TmAl$_2$, in Tm$_{0.1}$Al$_{0.9}$, and in TmB$_{12}$. The last source has the highest $f_s$.[34,35]

[p] The parent nucleus $^{181}$W is obtained by $^{180}$W(n,γ) $^{181}$W, $^{181}$Ta(d,2n) $^{181}$W or $^{181}$Ta(p,n) $^{181}$W reactions. The difficulties in preparing a good source lie in the large quadrupole moment of $^{181}$Ta, hence, any electric field gradients produced by impurities and lattice imperfections cause an appreciable broadening of the emission line, as compared with a very small value of $\Gamma_{nat}$. From among the different source matrices used, the most suitable is a tungsten matrix.[36]

[q] This level may be populated by β -decay of $^{182}$Ta produced by $^{181}$Ta(n,γ) $^{182}$Ta or $^{181}$Ta(d,p) $^{182}$Ta reactions, or by Coulomb excitation. The commonly used radioactive source is $^{182}$Ta in cubic Ta lattice. This gives a single line very close in width to $\Gamma_{nat}$ and has a reasonably high $f_s$ at low temperatures. In the case of Coulomb excitation, the W targets emit slightly broadened single lines and have a lower $f_s$ as a result of radiation damage or localized heating effects.[37,38]

[r] The parent nucleus $^{193}$Os is produced by $^{192}$Os(n,γ) $^{193}$Os reaction. Owing to the non-zero electric field gradient at the nuclear sites in the hexagonal osmium lattice, the emission line of the commonly used source $^{193}$Os in Os is an unresolved quadrupole doublet. The sources of $^{193}$Os in Pt, Nb and V emit sharper lines.[39]

## Table 6 (continued)
## SOURCE MATERIALS AND THEIR PROPERTIES

[s] This level is populated by electron capture decay of $^{195}$Au or by isomeric transition in $^{195m}$Pt. $^{195}$Au is produced by the $^{195}$Pt(d,2n) $^{195}$Au or $^{195}$Pt(p,n) $^{195}$Au reaction, and $^{195m}$Pt may be obtained by $^{194}$Pt(n,$\gamma$) $^{195m}$Pt reaction. The main disadvantage of the very often used sources $^{195}$Au in Pt, $^{195m}$Pt in Pt is the resonance self-absorption in the source matrix. The disadvantage mentioned above is avoided by using Ir and Cu matrices. The $^{195}$Au in Ir, $^{195}$Au in Cu sources emit single, only slightly broadened lines.[40,41]

[t] The 77.35 keV level may be populated by $\beta^-$-decay of $^{197}$Pt, obtained by $^{196}$Pt(n,$\gamma$) $^{197}$Pt reaction, or electron capture of $^{197}$Hg, produced by $^{196}$Hg(n,$\gamma$) $^{197}$Hg. The $^{197}$Pt parent nucleus is widely used because it gives a simpler photon spectrum than $^{197}$Hg. The best matrix for $^{197}$Pt is Pt. The linewidth of such source at 4.2 K is very close to $\Gamma_{nat.}$[42]

[u] The 59.54 keV level of $^{237}$Np may be populated by $\beta^-$-decay of $^{237}$U, produced by $^{236}$U(n,$\gamma$) reaction, $\alpha$-decay of $^{241}$Am, and electron capture of $^{237}$Pu, obtained via $^{237}$Np(d,2n) $^{237}$Pu reaction, the latter not being employed because of difficulties in preparation. In almost all Mössbauer studies $^{241}$Am parent nucleus is employed because of its longer half-life and cleaner gamma-spectrum as compared with $^{237}$U. $^{241}$AmO$_2$ in NpO$_2$, $^{237}$UO$_2$ in NpO$_2$, $^{241}$Am in Am and in Cu give single lines thirty times broader in width than $\Gamma_{nat}$. $^{241}$Am in non-metallic compound AmO$_2$ shows multiple emission lines. The best source thus far is $^{241}$Am in Th, giving the narrowest line which is still more than 15 times broader than $\Gamma_{nat}$.[43]

Footnotes for isotopes in Table 6 contain details of source preparation plus relevant references. Other information and references on those sources which may be of special interest to the readers are available from the author.

## VII. HAMILTONIANS

J. M. Trooster

### Introduction

The interactions of importance for the Mössbauer spectroscopist are the so-called "hyperfine interactions": the interactions between the nuclear moments (magnetic and electric) and the surrounding electrons.

The Hamiltonians describing these interactions are extensively treated in textbooks on Nuclear Magnetic Resonance, Electron Paramagnetic Resonance, and Mössbauer Spectroscopy.[45-47] In this section, the Hamiltonians of the hyperfine interactions will be given (without derivation) to define the constants listed elsewhere in this chapter.

### Zeeman Interaction

The energy of a nuclear magnetic moment $\bar{\mu}$ in a uniform magnetic field $\bar{B}$ is given by:

$$\mathcal{H}_Z = -\bar{\mu}\cdot\bar{B} \tag{10}$$

The magnetic moment is proportional to the spin $\bar{I}$:

$$\bar{\mu} = \gamma\hbar\bar{I} \tag{11}$$

giving:

$$\mathcal{H}_Z = -\gamma\hbar\bar{I}\cdot\bar{B} \tag{12}$$

If the z-axis is chosen to coincide with the direction of the magnetic field:

$$\begin{aligned}\bar{B} &= (0, 0, B)\\ \mathcal{H}_Z &= -\gamma\hbar B I_Z\end{aligned} \tag{13}$$