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# Low-intensity gamma rays in the decay of $^{166m}$Ho.

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# Low-intensity gamma rays in the decay of $^{166m}$Ho

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Using an anti-Compton spectrometer, the gamma ray spectrum of $^{166m}$Ho has been remeasured with the aim to reveal new low-intensity gamma transitions, since $^{166m}$Ho is a recommended calibration standard for Ge(Li) or HPGe detectors. Altogether 61 gamma transitions have been assigned to the $^{166m}$Ho decay. All of them have been established in the decay scheme.

$^{166m}$Ho was recognized as a suitable source for the calibration of semiconductor detectors, since it has a very long half-life (1200 y) and it emits many well separated and fairly strong gamma rays in the range from 80 to 1450 keV. Several measurements of gamma rays from $^{166m}$Ho have been performed since 1970 [1-7]. However, not all possible transitions between well-established $^{166}$Er excited levels were observed there. From the other side, the gamma ray spectrum of a nuclide, recommended as a calibration standard, should be known as completely as possible. Therefore, we decided to remeasure the $^{166m}$Ho decay with the aim to reveal weak missing gamma transitions.

After our measurements had been completed, the paper of T.

Ogandaga, J. Dalmasso and G. Ardisson [8] , with the same aim of investigation, got at our disposal. Their results are discussed below.

$^{166m}$Ho activity was obtained by irradiation of 100 mg $Ho_2O_3$ in the VVR-S nuclear reactor at Řež. After 10 month of cooling, the target was dissolved in hydrochloric acid and the material was purified by an extraction chromatography using di-(2-ethylhexyl) phosphoric acid as a stationary phase. The final form of the preparation was $HoF_3$.

The measurements of gamma rays were performed using a Ge(Li) -NaI(Tl) anti-Compton spectrometer [9,10] of the Konijn type [11]. The ralative efficiency of the Ge(Li) detector was 6 % and the resolution (FWHM) was 2.25 keV at 1332 keV. The Ø 254 mm x 200 mm NaI(Tl) scintillator was used as the anticoincidence shield. The measurements were done at a distance of 25 cm from the detector axis. The count rate was about 1500 cps. The background count rate was 12 cpm.

The energy calibration was performed, making use of the energy values of strong gamma lines of the source itself. These values were taken from the $^{166}$Tm decay [12] and they were determined, in their turn, with the aid of standard sources $^{54}$Mn, $^{57}$Co, $^{60}$Co, $^{75}$Se and $^{169}$Yb [13]. However, they cover the range from 80 to 900 keV only. In the range above 900 keV, the energies of $^{166m}$Ho gamma rays given by Sooch et al. 7 were used.

The efficiency curve of the detector was established, using standard sources of $^{56}$Co, $^{75}$Se, $^{110m}$Ag, $^{152}$Eu and $^{169}$Yb [13], with the error not exceeding 2 % over the whole range of our present measurements. The self-absorption in the source was taken into account. No corrections were made for coincidence summing because of the large distance from the source to the detector.

The gamma ray spectrum of $^{166m}$Ho obtained in a 300 hours' run is shown in fig.1. No gamma rays were observed which could be attributed to other activities.

The energies and relative intensities of the $^{166m}$Ho gamma rays are listed in table 1. The asterisks denote those weak gamma transitions, which were not observed in works [1-7] . The results of Ogandaga et al [8] are also shown in table 1 for comparison. 100 % of decays correspond to 136.3 ( 19) intensity units of this table. It is the mean value obtained from the intensity balance for the 0.0,80.583 and 264.988 keV levels as well as from the total intensity of beta transitions feeding the $I^{\pi} = (6,7,8)^{\pm}$ levels.

The decay scheme of $^{166m}$Ho is shown in fig. 2. It includes all transitions listed in table 1 (see collumns 5 and 6 of the table indicating their placements in the sheme) . Thorough inspection of the level scheme led us to the conclusion that four of the gamma rays listed, namely 215.75, 410.995, 616.077 and 736.653 keV, should be doublets in fact. Their decomposition into components is made in table 2. The energies of the components are derived from the level scheme. In the case of the 215.75 keV line, the ratio of the intensities of its components is the mean value taken from refs. [5-7]. In each of the other cases, the relative intensity of that component, which is known from the $^{166}$Tm decay, is calculated from the $^{166}$Tm data [12], using branching ratios of transitions deexciting corresponding levels. The remaining intensity is then ascribed to the second component appearing in the $^{166m}$Ho decay only.

A number of sum peaks was identified in the gamma ray spectrum. Therefore,a thorough analysis of this effect was undertaken. It was based on the decay scheme presented in fig. 2, on the time resolution $2\tau = 4.9\times10^{-7}$s of our setup for $E_\gamma > 180$ keV and on the absolute efficiency of our detector for the given geometry, which was $1.3\times10^{-4}$ for 662 keV. The areas of all sum peaks but two were found to be consistent with the calculated estimations. The two exceptions are the peaks observed at 1521.78(6) and 1562.32(7) keV. Their areas (in counts) were measured to be 9331 ± 102 and 2199 ± 50, respectively. From this, 4771 ± 483 and 1217 ± 125 are due to summing effects and the remainder should be ascribed to the cross-over transitions with corresponding relative intensities given in table 1. Both transitions are of the M2 ($6^- \rightarrow 4^+$) type. According to our estimation, they are hindered approximately $10^2$-times, as compared to the Weisskopf model [14]. Such values of the hindrance factors are quite usual. Our estimation is based on the assumption, that the competing E2 transitions are realized between rotational states and are enhanced. As to the energies of both peaks, they are some 200 eV lower than they should be according to the decay scheme what is charakteristic for all peaks with large summirg component.

As it can be seen from table 1, the results of Ogandaga et al. [8] agree, in general, quite satisfactorily with ours. However, significant discrepancies appear in several cases. The intensities of the 616 keV gamma transition differ almost 4 times. However, our value is in correspondence with the intensity ratio $I_{\gamma 615}/I_{\gamma 497} = 0.77(4)$, known from the $^{166}$Tm decay [12]. In the case of the 1307 and 1331 transitions, our intensities are only half the values given in ref. [8]. A gamma line at 1261.98 keV was observed in ref. [8], which was identified with the gamma ray known from the $^{166}$Tm decay, deexciting the 1527 keV $2^+$ level. The upper limit is given for the 1447 keV transition deexciting the same level. We did not observed such lines and are able to give much lower limits of their intensities (see table 1). Therefore, we cannot confirm that the 1527 keV ($2^+$) level is fed in the $^{166m}$Ho decay. Close to 1262 keV, sum peaks 1261.813 keV = = 451.531 keV+ 810.282 keV and 1262.294 keV = 571.034 keV + + 691.260 keV can be expected to appear. In conditions of our experiment, the sum of the relative intensities of both of these sum peaks should be 0.0006 (in the units of table 1).

Preliminary results of our measurements were published in [15]. More detailed discussion concerning the decay scheme of $^{166m}$Ho and the structure of $^{166}$Er excited levels forms the subject of another paper [16].

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Table 1

Energies and relative intensities of the gamma rays from the $^{166m}$Ho decay.

| Energy (keV) | | Relative intensity a) | | Assignment | |
|---|---|---|---|---|---|
| This work | Ogandaga et al. [8] | This work | Ogandaga et al. [8] | From($I^\pi$,K) | To ($I^\pi$,K) |
| 80.585(15) | 80.56(1) | 17.2(7) | 16.97(13) | $2^+$ , 0 | $0^+$ , 0 |
| 94.697(23) | 94.70(1) | 0.190(25) | 0.20(1) | $6^-_1$ , 4(2) | $5^-_2$ , 2(4) |
| 119.09(4) | 119.07(1) | 0.243(12) | 0.24(1) | $5^+$ , 2 | $4^+$ , 2 |
| 121.209(26) | 121.20(1) | 0.346(12) | 0.35(2) | $6^-_1$ , 4(2) | $5^-_1$ , 4(2) |
| 135.275(26) | 135.30(2) | 0.128(5) | 0.14(1) | $6^-_2$ , 2(4) | $5^-_2$ , 2(4) |
| 140.73(4) | 140.72(2) | 0.060(3) | 0.07(1) | $6^+$ , 2 | $5^+$ , 2 |
| 160.09(3) | 160.09(2) | 0.124(8) | 0.14(2) | $7^+$ , 2 | $6^+$ , 2 |
| 161.78(3) | 161.78(2) | 0.140(6) | 0.15(2) | $6^-_2$ , 2(4) | $5^-_1$ , 4(2) |
| 184.405(15) | 184.41(1) | 100.0(20) | 100 | $4^+$ , 0 | $2^+$ , 0 |
| 190.759(29) | 190.80(3) | 0.291(9) | 0.33(2) | $6^-_1$ , 4(2) | $4^-_2$ , 2 |
| 215.75(25) b) | 214.79(2)<br>215.90(1) | 4.14(15) | 0.61(2)<br>3.60(13) | $6^-_1$ , 4(2)<br>$5^+$ , 2 | $4^-_1$ , 4<br>$3^+$ , 2 |
| 231.322(26) | 231.31(2) | 0.289(9) | 0.33(3) | $6^-_2$ , 2(4) | $4^-_2$ , 2 |
| 255.20(12) *) | | 0.0059(13) | | $6^-_2$ , 2(4) | $4^-_1$ , 4 |
| 259.717(18) | 259.76(2) | 1.47(4) | 1.52(3) | $6^+$ , 2 | $4^+$ , 2 |
| 280.450(26) | 280.46(1) | 40.4(13) | 40.6(5) | $6^+$ , 0 | $4^+$ , 0 |
| 300.730(24) | 300.77(1) | 5.04(16) | 5.11(8) | $7^+$ , 2 | $5^+$ , 2 |
| 304.82(4) *) | 305.03(5) | 0.030(3) | 0.023(3) | $6^+$ , 2 | $8^+$ , 0 |
| 339.788(25) | 339.71(3) | 0.222(7) | 0.21(3) | $8^+$ , 2 | $6^+$ , 2 |
| 365.741(22) | 365.76(2) | 3.33(10) | 3.46(6) | $8^+$ , 0 | $6^+$ , 0 |
| 410.96(3) b) | 410.95(1) | 15.3(4) | 15.5(4) | see tab. 2 | |
| 451.531(26) | 451.53(2) | 4.00(11) | 4.04(11) | $6^-_2$ , 2(4) | $7^+$ , 2 |
| 464.825(20) | 464.76(2) | 1.59(4) | 1.73(7) | $7^+$ , 2 | $8^+$ , 0 |
| 476.37(4) *) | 476.38(6) | 0.050(3) | 0.052(6) | $5^-_2$ , 2(4) | $6^+$ , 2 |
| 496.935(19) | 496.86(4) | 0.170(5) | 0.17(1) | $4^-_1$ , 4 | $5^+$ , 2 |
| 520.99(4) | 520.85(5) | 0.20(3) | 0.21(1) | $4^-_2$ , 2 | $5^+$ , 2 |
| 529.835(18) | 529.76(2) | 12.83(29) | 13.18(34) | $5^+$ , 2 | $6^+$ , 0 |
| 571.034(18) | 570.94(2) | 7.42(18) | 7.64(20) | $6^-_1$ , 4(2) | $6^+$ , 2 |
| 590.67(15) *) | | 0.032(3) | | $5^-_1$ , 4(2) | $5^+$ , 2 |
| 594.423(25) | 594.52(3) | 0.769(18) | 0.80(9) | $3^+$ , 2 | $4^+$ , 0 |
| 611.615(26) | 611.49(3) | 1.85(6) | 1.86(12) | $6^-_2$ , 2(4) | $6^+$ , 2 |

Table 1 (continuation)

| Energy (keV) | | Relative intensity | | Assignment | |
|---|---|---|---|---|---|
| This work | Ogandaga et al. [8] | This work | Ogandaga et al. [8] | From($I^\pi$,K) | To($I^\pi$,K) |
| 616.08(8) b) *) | 615.84(5) | 0.163(7) | 0.044(13) | see tab. 2 | |
| 640.003(24) | 639.97(5) | 0.124(5) | 0.11(1) | $4^-_2$, 2 | $4^+$, 2 |
| 644.598(26) | 644.78(5) | 0.186(5) | 0.23(6) | $8^+$, 2 | $8^+$, 0 |
| 670.525(21) | 670.49(2) | 7.32(17) | 7.16(20) | $6^+$, 2 | $6^+$, 0 |
| 691.260(18) | 691.24(3) | 1.79(4) | 1.86(9) | $4^+$, 2 | $4^+$, 0 |
| 706.2 8 *) | 705.09(7) | 0.025(15) | 0.011(1) | $2^+$, 2 | $2^+$, 0 |
| 711.701(24) | 711.68(1) | 73.8(28) | 75.33(177) | $6^-_1$, 4(2) | $5^+$, 2 |
| 736.653(27) b) | 736.65(4) | 0.530(14) | 0.50(4) | see tab. 2 | |
| 752.281(19) | 752.30(2) | 16.5(4) | 17.08(43) | $6^-_2$, 2(4) | $5^+$, 2 |
| 778.818(18) | 778.82(2) | 4.13(10) | 4.22(14) | $3^+$, 2 | $2^+$, 0 |
| 785.90(7) *) | 785.81(7) | 0.023(3) | 0.019(4) | $2^+$, 2 | $0^+$, 0 |
| 810.282(16) | 810.27(1) | 78.2(20) | 79.31(177) | $5^+$, 2 | $4^+$, 0 |
| 830.583(18) | 830.58(2) | 13.3(3) | 13.51(35) | $7^+$, 2 | $6^+$, 0 |
| 875.658(21) | 875.69(4) | 0.987(24) | 1.00(5) | $4^+$, 2 | $2^+$, 0 |
| 950.955(28) | 950.97(3) | 3.74(9) | 3.87(12) | $6^+$, 2 | $4^+$, 0 |
| 1010.302(26) | 1010.27(6) | 0.107(3) | 0.13(3) | $8^+$, 2 | $6^+$, 0 |
| 1120.324(28) | 1120.35(5) | 0.268(6) | 0.28(5) | $5^-_1$, 4(2) | $6^+$, 0 |
| 1146.84(4) | 1146.83(5) | 0.279(7) | 0.29(4) | $5^-_2$, 2(4) | $6^+$, 0 |
| 1241.484(28) | 1241.47(4) | 1.118(25) | 1.21(6) | $6^-_1$, 4(2) | $6^+$, 0 |
| ~1262 | 1261.98(12) | <0.004 | 0.010(1) | | |
| 1282.08(4) | 1282.06(6) | 0.340(8) | 0.28(4) | $6^-_2$, 2(4) | $6^+$, 0 |
| 1307.30(8) *) | 306.16(15) | 0.0044(4) | 0.010(1) | $4^+_1$, 4 | $4^+$, 0 |
| 1331.45(14) *) | 1331.04(13) | 0.0051(6) c) | 0.010(1) | $4^-_2$, 2 | $4^+$, 0 |
| 1400.75(4) | 1400.76(5) | 0.672(16) | 0.76(4) | $5^-_1$, 4(2) | $4^+$, 0 |
| 1427.24(6) | 1427.17(5) | 0.673(17) | 0.77(4) | $5^-_2$, 2(4) | $4^+$, 0 |
| ~1447 | 1446.72(13) | <0.0006 | <0.01 | | |
| 1515.62(15) *) | | 0.0010(4) | | $4^-_2$, 2 | $2^+$, 0 |
| 1521.99(4) d) *) | | 0.018(5) | | $6^-_1$, 4(2) | $4^+$, 0 |
| 1562.57(4) d) *) | | 0.0040(11) | | $6^-_2$, 2(4) | $4^+$, 0 |

a) 100 % of decays = 136.3(19) rel. intensity units.
b) Doublet, see tab. 2.
c) Intensity of the possible 1332.50 keV $^{60}$Co component is less than 0.0017 rel. intensity units.
d) These energies are derived from the decay scheme.
*) Transitions not observed in refs. [1 - 7] .

Table 2.

Decomposition of close doublets.

| Energy [a] keV | Relative intensity | Assignment | | Energy [a] keV | Relative intensity | Assignment | |
|---|---|---|---|---|---|---|---|
| | | From $(I^\pi,K)$ | To $(I^\pi,K)$ | | | From $(I^\pi,K)$ | To $(I^\pi,K)$ |
| 214.76(5) | 0.59(2) [b] | $6^-_1,4(2)$ | $4^-_1,4$ | 215.88(3) | 3.55(2) [b] | $5^+, 2$ | $3^+, 2$ |
| 410.80(5) | 0.0230(12) [c] | $4^+,2$ | $6^+,0$ | 410.95(3) | 15.24(4) | $6^-_1, 4(2)$ | $7^+, 2$ |
| 615.96(3) | 0.132(9) [c] | $4^-_1,4$ | $4^+,2$ | 617.0(5) | 0.031(9) | $5^-_2, 2(4)$ | $5^+, 2$ |
| 736.02(8) | 0.19(2) | $5^-_2,2(4)$ | $4^+,2$ | 736.83(3) | 0.34(2) [c] | $4^-_2, 2$ | $3^+, 2$ |

a) The energies are derived from the decay scheme.

b) The ratio of the intensities of these two components is taken from refs. [5-7].

c) The intensity of this component is derived from the $^{166}$Tm data [12].

## Figure captions

Fig. 1. Gamma ray spectrum of $^{166m}$Ho measured with an anti-Compton spectrometer.

Fig. 2. Level scheme of $^{166}$Er populated in the decay of $^{166m}$Ho.

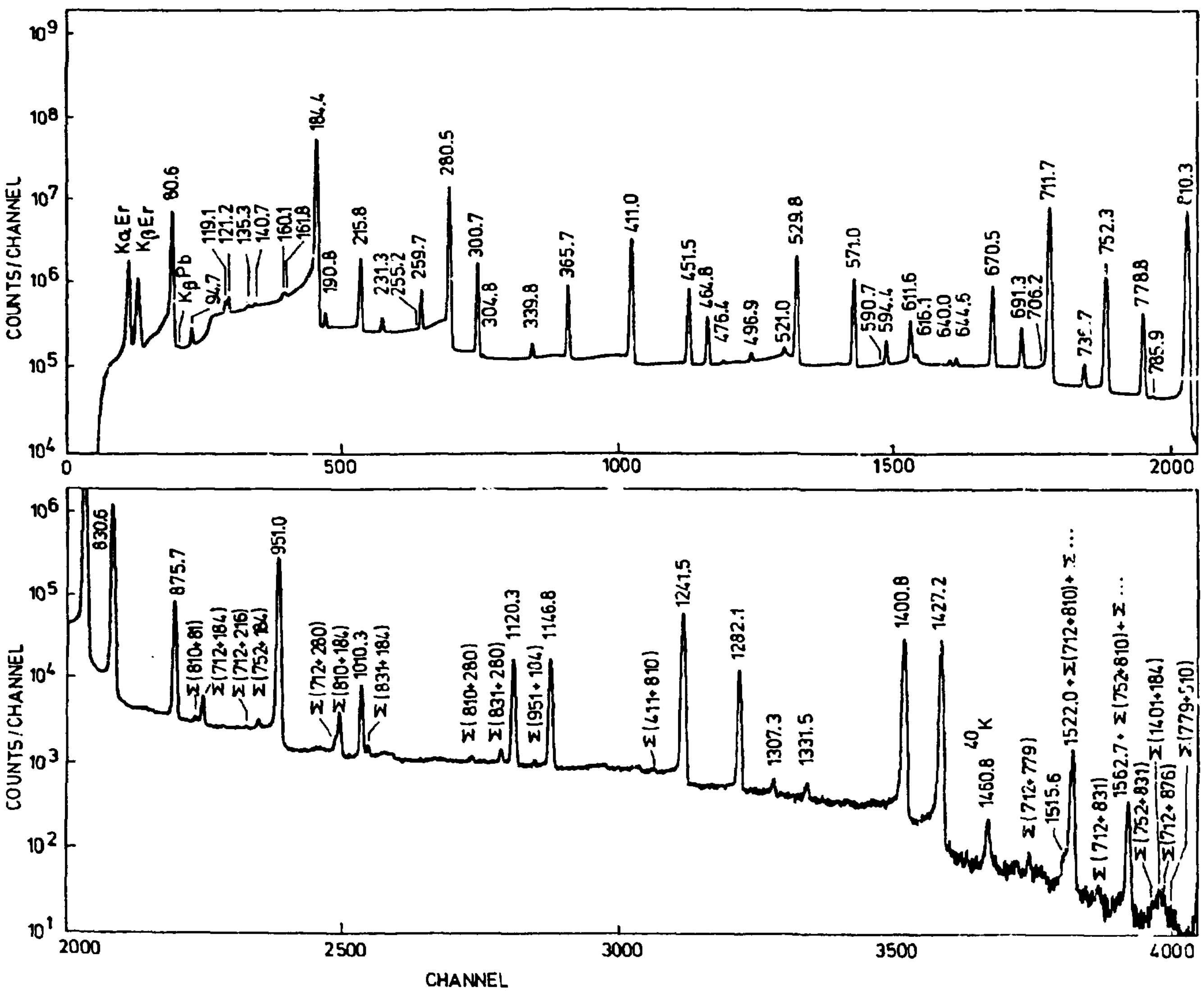
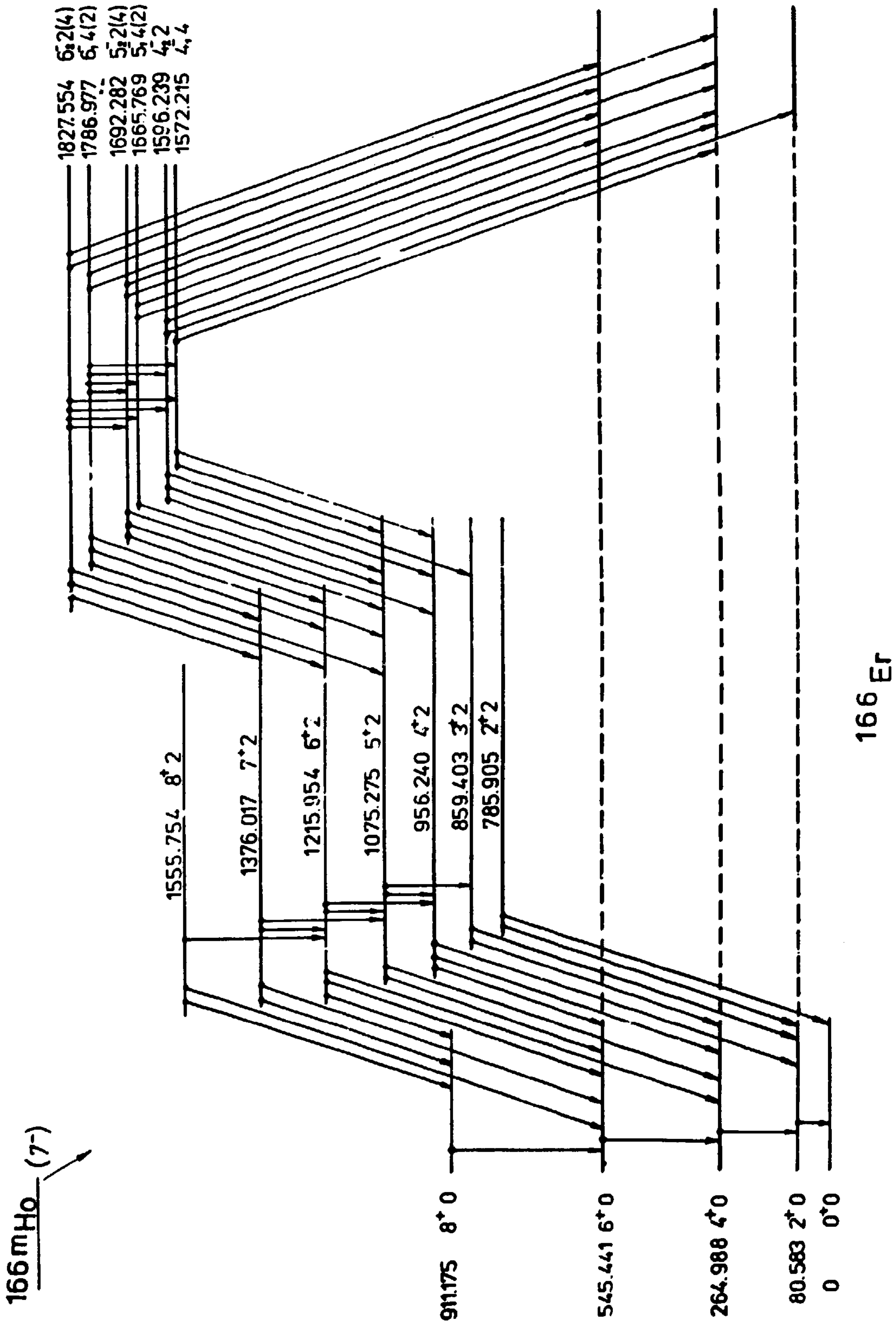

COUNTS/CHANNEL
10^4
10^5
10^6
10^7
10^8
10^9
0
500
1000
1500
2000
KαEr
KβEr
80.6
KβPb
94.7
119.1
121.2
135.3
140.7
160.1
161.8
184.4
190.8
215.8
231.3
255.2
259.7
280.5
300.7
304.8
339.8
365.7
411.0
451.5
464.8
476.4
496.9
521.0
529.8
571.0
590.7
594.4
611.6
616.1
640.0
644.6
670.5
691.3
706.2
711.7
73?.7
752.3
778.8
785.9
810.3
COUNTS/CHANNEL
10^1
10^2
10^3
10^4
10^5
10^6
2000
2500
3000
3500
4000
CHANNEL
830.6
875.7
Σ(810+81)
Σ(712+184)
Σ(712+216)
Σ(752+184)
951.0
Σ(712+280)
Σ(810+184)
1010.3
Σ(831+184)
Σ(810+280)
Σ(831+280)
1120.3
Σ(951+104)
1146.8
Σ(411+810)
1241.5
1282.1
1307.3
1331.5
1400.8
1427.2
1460.8 40K
Σ(712+779)
1515.6
1522.0+Σ(712+810)+Σ...
Σ(712+831)
1562.7+Σ(752+810)+Σ...
Σ(752+831)
Σ(1401+184)
Σ(712+876)
Σ(779+510)

Fig. 1.

Fig. 2.


166mHo
(7-)
911.175 8+ 0
545.441 6+ 0
264.988 4+ 0
80.583 2+ 0
0 0+ 0
1555.754 8+ 2
1376.017 7+ 2
1215.954 6+ 2
1075.275 5+ 2
956.240 4+ 2
859.403 3+ 2
785.905 2+ 2
1827.554 6- 2(4)
1786.977 6- 4(2)
1692.282 5- 2(4)
1665.769 5- 4(2)
1596.239 4- 2
1572.215 4- 4
166Er