EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

THE DECAY PROPERTIES OF ^{206}Hg, AND THE ^{208}Pb(p,3p)^{206}Hg REACTION

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ABSTRACT

^{206}Hg was produced by the ^{208}Pb(p,3p)^{206}Hg reaction and its decay properties were investigated. The half-life was determined to 8.15 ± 0.1 min. Gamma, beta and conversion electron spectra were measured. It was found that the beta decay of ^{206}Hg leads to the ground state (60%), to a 305 keV state (35%) and to a 650 keV state (5%) of ^{206}Tl. The spins and parities assigned to these states are 0^-, 1^-, 1^- respectively. No evidence of a low-lying state ($\leq$ 10 keV) of ^{206}Tl, predicted by shell-model calculations, was found.

Cross-section measurements for the ^{208}Pb(p,3p)^{206}Hg reaction with 590 MeV and 19 GeV protons gave values of 600 μbarns and 260 μbarns.

Geneva - May 1968

(to be submitted to Nuclear Physics)

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1. INTRODUCTION

^{206}Hg was first found by Nurmia et al.[1]. Investigating a ^{210}Pb source, they detected a small α-branching to a β-emitter with a half-life of 7.5 minutes. Larger amounts of ^{206}Hg were produced by the ^{208}Pb(p,3p)^{206}Hg reaction. Since a large number of neutron deficient mercury isotopes arises from proton bombardment of lead, the identification of ^{206}Hg was only possible by milking the daughter ^{206}Tl($T_{1/2}$ = 4.2 min). In this experiment a half-life of 8.5 ± 0.1 min was measured[2]. Wolf, Lux and Born[3] isolated ^{206}Hg from strong ^{210}Pb sources and found a half-life of 8.1 ± 0.4 min and a γ-line of 310 ± 10 keV.

In all these experiments the activity was not sufficient for detailed spectroscopic investigations of the decay properties of ^{206}Hg. Such investigations are specially interesting, because the decay of ^{206}Hg gives some information about the energy levels of ^{206}Tl, which is an odd-odd nucleus with one neutron and one proton hole with respect to the doubly magic ^{208}Pb. The level-scheme of ^{206}Tl has been investigated in the α-decay of ^{210m}Bi[4,5] as well as by the ^{205}Tl(d,p)^{206}Tl reaction[6,7]. Calculations on the basis of the shell model have also been performed[8,9]. Some serious discrepancies between the shell-model calculations and experimental results will be discussed later. In the present work we produced ^{206}Hg by the ^{208}Pb(p,3p)^{206}Hg reaction and performed a fast mass separation. Sufficient ^{206}Hg ($\approx$ 1 μCi) for spectroscopic investigations was obtained. In addition, the cross-sections for the production of ^{206}Hg with 600 MeV and 18 GeV protons were measured, since only very little is known about (p,3p) cross-sections in the heavy element region[10].

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2. EXPERIMENTAL PROCEDURE

2.1 Irradiations

For the production of ^{206}Hg for spectroscopic investigations lead foils of thickness 80 mg/cm^2 were used as targets. For the cross-section measurements three such lead foils were mounted in a stack with three aluminium foils on each side, the middle ones 10 μ and the others 30 μ thick. The middle aluminium foils were used as beam monitors. The targets were irradiated for 10 to 20 minutes with 590 MeV protons of the CERN Synchro-cyclotron and with 19 GeV protons of the CERN Proton Synchroton.

2.2 Separation procedures

2.2.1 Samples for spectroscopic investigations

The irradiated lead foils were transported as fast as possible to a thermostatically-controlled heated glass vessel, which was connected to the ion source of the CERN isotope separator[11] by means of a heated tube. By heating the foil under vacuum to the melting point of lead, the mercury evaporated, while the other elements formed during irradiation remained in the lead. The mass-separated ^{206}Hg was collected on an aluminium foil and measured immediately after the end of the separation. The measurements were started 15 to 20 minutes after the end of the irradiation. The overall ^{206}Hg yield of the procedure, corrected for losses by decay, was 5 to 10%.

2.2.2 Samples for cross-section measurements

In this case the procedure given in section 2.2.1 was not practicable, since the yields were not exactly reproducible. Hence we used the following method: The middle one of the three lead foils was dissolved in 15 ml 6 N HNO_3 which contained 0.5 mg mercury carrier and 5 μCi ^{203}Hg as tracer for the yield determination. The bulk of the lead was precipitated with 4 ml of a saturated Na_2SO_4 solution. The mercury in the filtrate was then precipitated with 200 mg $SnCl_2$ in 0.5 ml 6 N HCl, filtered, and washed with ethanol and ether. The filter with the mercury was introduced into the glass vessel on the isotope separator, as described above, and heated to 100°C. At this temperature the mercury evaporated and was fed into the isotope separator. The yield of the chemical procedure and the

isotope separation was determined by measuring the ^{203}Hg activity on the collector foils, assuming that the isotope separator yield is the same for all Hg isotopes[12].

The over-all yield for the different experiments, corrected for losses by decay, was 0.1 to 0.2 %. The time between the end of the irradiation and the start of the measurements was 30 to 40 minutes.

2.3 Measurements

Beta measurements were done with a calibrated methane-flow proportional counter. Gamma spectra were measured with a 3" × 3" NaI(Tl) crystal and a 30 cm^3 coaxial Ge(Li) detector. For β-γ-coincidence measurements we used a 6" × 4" NaI(Tl) crystal in combination with a 5 mm Si(Li) detector, and for γ-γ-coincidence measurements an arrangement consisting of two 1.5" NaI(Tl) crystals. As detector for conversion electrons a Si(Li) detector with an area of 50 mm^2 (2 mm thick) was used.

3. RESULTS

3.1 Half-life

Figure 1 shows the beta decay of a ^{206}Hg sample, measured from 25 to 220 min after the end of the irradiation. The initial deviation from a straight line is caused by the growing in of ^{206}Tl ($T_{1/2}$ = 4.2 min), which starts during the mass separation. The long-lived background is caused by contaminations of other mercury isotopes. A computer analysis of the decay curve gave a half-life of 8.15 ± 0.1 min in good agreement with earlier measurements[2,3].

3.2 Gamma energies

Figure 2 shows the gamma spectrum of ^{206}Hg, obtained with a NaI(Tl) crystal in 30 min. The three peaks can be assigned to the X-ray line, the ^{206}Hg main gamma line (303 ± 3 keV) and a gamma line of 650 ± 5 keV. All three lines decay with the half-life characteristic for ^{206}Hg. The daughter ^{206}Tl, which is present in the sample, has no gamma transitions[13].

The gamma spectrum, measured with a Ge(Li) detector is shown in Fig. 3, showing again the X-ray line and the main ^{206}Hg gamma line of 305 ± 2 keV.

In the 650 keV region there is no pronounced peak, because of the relatively poor counting statistics, but the number of counts in this region is bigger than the average number of background counts. Coincidence measurements between the 650 keV and the 305 keV gamma-rays showed that the two gamma quanta are not emitted in coincidence.

3.3 Conversion coefficient

The conversion electrons emitted in the decay of ^{206}Hg have their origin almost completely in the conversion of the 305 keV gamma quanta. It is therefore possible to calculate the K-conversion coefficient (α_K) of this transition from the ratio of the intensities of the K X-rays and the 305 keV gamma quanta.

$$\alpha_K = \frac{N_X}{N_\gamma \cdot W_K}$$

where

N_X = number of X-ray quanta

N_γ = number of gamma quanta

W_K = K-shell fluorescence yield

If we take W_K from literature[14] (0.95) and N_X and N_γ from the spectrum in Fig. 2, and correct for the efficiency of the detector, we get a K-conversion coefficient of 0.28 ± 0.05.

3.4 Beta to gamma ratio

To get the number of beta decays of ^{206}Hg relative to the number of 305 keV and 650 keV gamma quanta, the decay of one sample was measured alternately with a beta counter and a NaI(Tl) crystal of known efficiency. The number of gamma quanta emitted per time unit at the end of the irradiation could be extrapolated from the decay of the 305 keV and 650 keV peaks.

The total number of ^{206}Hg decays was calculated from the beta decay curve, knowing the half-lives of ^{206}Hg and ^{206}Tl, and the efficiency of the beta counter for all energies. Since the 350 keV and 650 keV gamma quanta are not emitted in coincidence, the comparison of the number of

the beta decays with the number of gamma quanta, taking into consideration the conversion coefficient gave the following result: 5 ± 2 % of the beta decays of ^{206}Hg populate the 650 keV level, 35 ± 7 % the 350 keV level, and 60 ± 12 % the ground state of ^{206}Tl.

3.5 Beta energies

The beta spectrum of a ^{206}Hg sample, measured with a Si(Li) detector, could not be analysed, since it was composed of the three beta groups of ^{206}Hg itself and the 1.52 MeV beta group of ^{206}Tl. Therefore, coincidence measurements between the 305 keV gamma line and the corresponding beta particles were made. The counting statistics were too poor to analyse the shape of the spectrum, but the data were sufficient to determine the end point energy by means of a Kurie plot computer program[15]. The calculated value of $E_{\beta max}$ = 935 ± 62 keV is in good agreement with the value of 1.0 MeV, estimated from a closed decay cycle[3].

3.6 Conversion electron energies

Figure 4 shows the conversion electron spectrum of ^{206}Hg with three peaks of 220 keV, 290 keV, and 303 keV. The energies correspond to the energies of K-, L-, M-conversion of the 305 keV gamma quanta. The K:L:M ratio is 1:0.2:0.04 approximately. Conversion electrons of the 650 keV gamma quanta could not be detected.

4. DISCUSSION OF THE DECAY PROPERTIES OF ^{206}Hg AND THE ENERGY LEVELS OF ^{206}Tl

From the results of our measurements we suggest a decay scheme as given in Fig. 5. The log ft values for the three beta transitions are 5.3, 5.4, and 5.5, and are therefore characteristic for allowed transitions (ΔJ = 0,1; no parity change). The ^{206}Hg ground state is $J^{\pi} = 0^{+}$, and therefore the ^{206}Tl states should also have even parity. On the other hand the shell model predicts strictly odd parity[6,7,8,9,16] for the low-lying states of ^{206}Tl. Since first forbidden transitions (ΔJ = 0,1; parity change) with unusually low log ft values appear frequently in this mass region[2], we can assume that the beta transitions of ^{206}Hg belong to this group. The corresponding ^{206}Tl levels should then be $J^{\pi} = 0^{-}$ or 1^{-}. The fact that there exists no transition from the

^{206}Tl ground state to the 803 keV 2^+ state of ^{206}Pb, and the results of the ^{205}Tl(d,p)^{206}Tl experiments of Mukherjee[6] and Erskine[7] are strong arguments for a 0^- spin assignment to the ^{206}Tl ground state. The 305 keV state must then have spin 1^- because the K-conversion coefficient of 0.28 ± 0.05 and the K:L:M ratio of 1:0.2:0.04 is in good agreement with the theoretical values (0.32, 1:0.16:0.06) for M1-transitions[17], whereas the values for other cases are very different. The 650 keV state must also have spin 1^-, since the log ft value of the beta branching feeding this level is too low for assignments as 2^- or 3^-; moreover with the latter assignments the probability for a gamma transition to the 305 keV state would be bigger than for the transition to the ground state, which is obviously not the case. Figure 6 shows the spin assignments from the present work in comparison with the data from ^{205}Tl(d,p)^{206}Tl studies[6,7] and alpha decay studies of ^{210m}Bi[4,5].

The present data on the ground state and the 305 keV state are in excellent agreement with the results of Erskine[7], of Mukherjee[6], and of Rusinov[4] and Spejewski[5]. Erskine suggested for the 650 keV state a spin of 2^- or 3^-. The data of Mukherjee and Spejewski correspond better with an assignment 1^-. The present results show that 1^- is the most probable value for the 650 keV state. The present work as well as all other experimental studies are in disagreement with the shell-model calculations on ^{206}Tl[7,8,9,16]. From Fig. 6, it looks as if the 0^- ground state and the 1^- 305 keV state should be the two members of the ground state doublet, predicted by the calculation. But the energy difference between the two states is quite large compared with the calculations, which predict only a small fraction of the observed difference. It was therefore suggested by Rusinov et al.[4] and by Kharitonov et al.[8] that the doublet splitting might be so small ($\leq$ 10 keV), that it was overlooked in the experiments. Assuming such a configuration, the probability for gamma transitions and conversion electron transitions from the 305 keV state to the ground state is about as big as to the "$\leq$ 10 keV state". That means that the spectra should have two peaks with $\leq$ 10 keV energy difference. Figures 3 and 4 show only one peak. Since the resolution was about 7 keV in both cases we can exclude the existence of a low-lying state $\geq$ 7 keV. Whether a state of still lower energy exists or not

can be confirmed only by high resolution spectrometry on much stronger samples than the ones which were available for the present work. We are preparing such experiments on the isotope separator on-line with the CERN Synchro-cyclotron (ISOLDE).

5. CROSS-SECTIONS OF THE $^{208}Pb(p,3p)^{206}Hg$ REACTION AT 590 MeV AND 19 GeV

The separated ^{206}Hg samples were measured with a proportional gas-flow counter of known efficiency. The bata decay curves were analysed by a computer program and the saturation activity calculated as described in Section 3.4, considering the chemical and mass separator yield. The proton flux was determined by the $^{27}Al(p,3pn)^{24}Na$ reaction ($\sigma_{590\ MeV}$ = 11 mbarns; $\sigma_{19\ GeV}$ = 8.6 mbarns[18]). The ^{24}Na saturation activity was calculated from the measurements of the 2.75 MeV gamma line with a NaI(Tl) crystal of known efficiency.

The cross-sections for the $^{208}Pb(p,3p)^{206}Hg$ reaction, computed from these data, were 600 ± 180 μbarns for 590 MeV protons and 260 ± 80 μbarns for 19 GeV protons. The results show that the cross-sections for the (p,3p) reaction with protons of high energy ($\geq$ 300 MeV) are only very little energy-dependent in this mass region. Caretto[10] and Porile[19] got similar results for the (p,3p) cross-sections for the interaction of 100 to 400 MeV protons with ^{186}W and ^{187}Re, and 0.5 to 3 GeV protons with ^{69}Ga respectively.

Acknowledgements

The author wishes to thank CERN for allowing him the possibility to work for some time with the Nuclear Chemistry Group, Mr. A. Kjelberg for his kind support of this work, and Mr. G. Astner for useful discussions. He is deeply indebted to Miss I. Jarstorff, Mrs. R. Mohr and Mrs. W. Stoetzel for their invaluable assistance and to Mr. G. Droz and Mr. S. Sundell for the performance of the isotope separations.

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Figure captions

Fig. 1 : Beta decay of ^{206}Hg-^{206}Tl, measured with a proportional counter. The time scale is in hours after end of irradiation.

Fig. 2 : Gamma spectrum of ^{206}Hg measured with a NaI(Tl) crystal.

Fig. 3 : Gamma spectrum of ^{206}Hg measured with a Ge(Li) detector.

Fig. 4 : Conversion electron spectrum measured with a Si(Li) detector.

Fig. 5 : Decay scheme of ^{206}Hg deduced from the data of this work.

Fig. 6 : Energy level diagrams of the low-lying levels in ^{206}Tl, as observed in the present study and reported by Rusinov et al.[4] Spejewski[5] and Erskine[7].

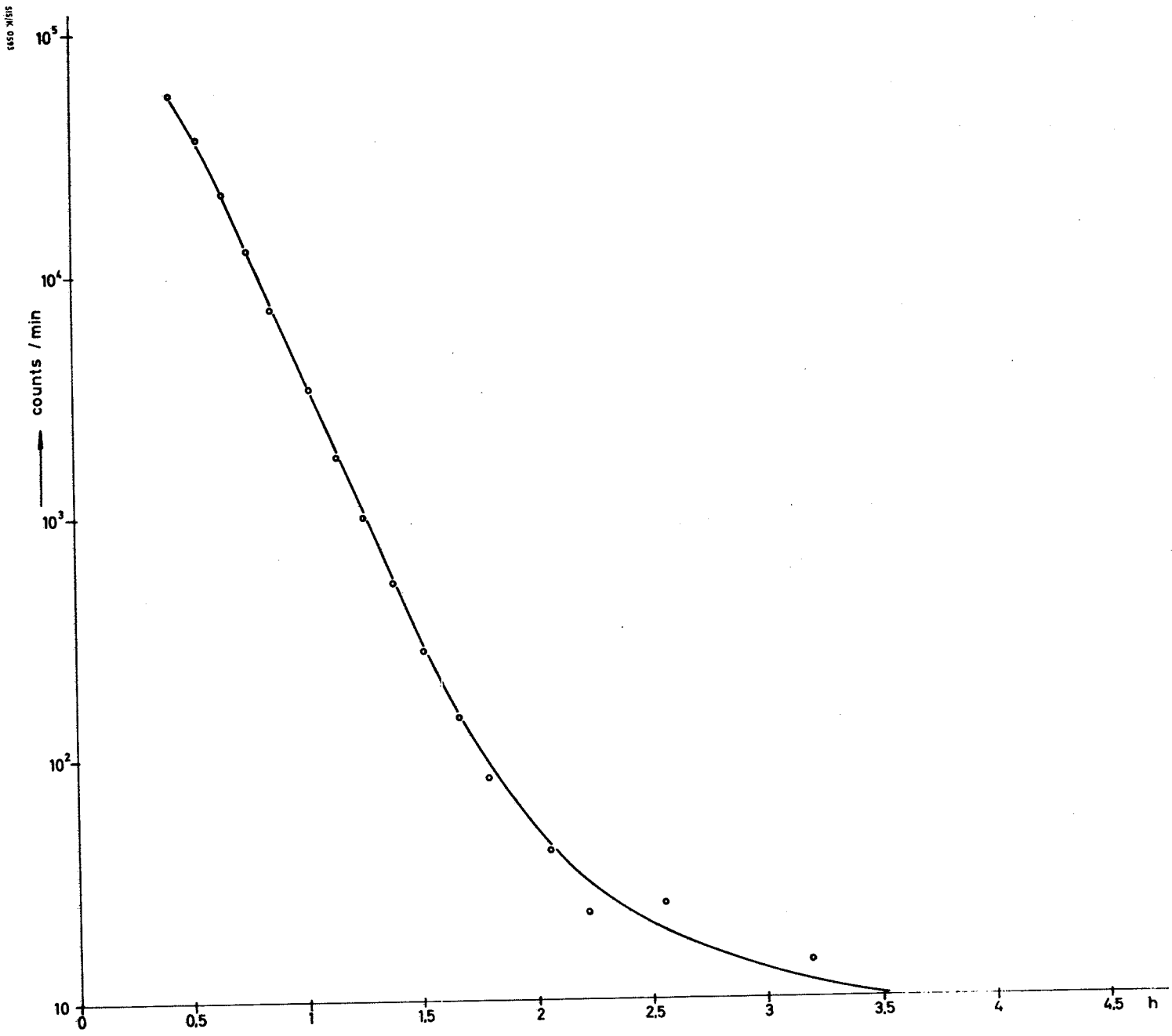

Fig 1

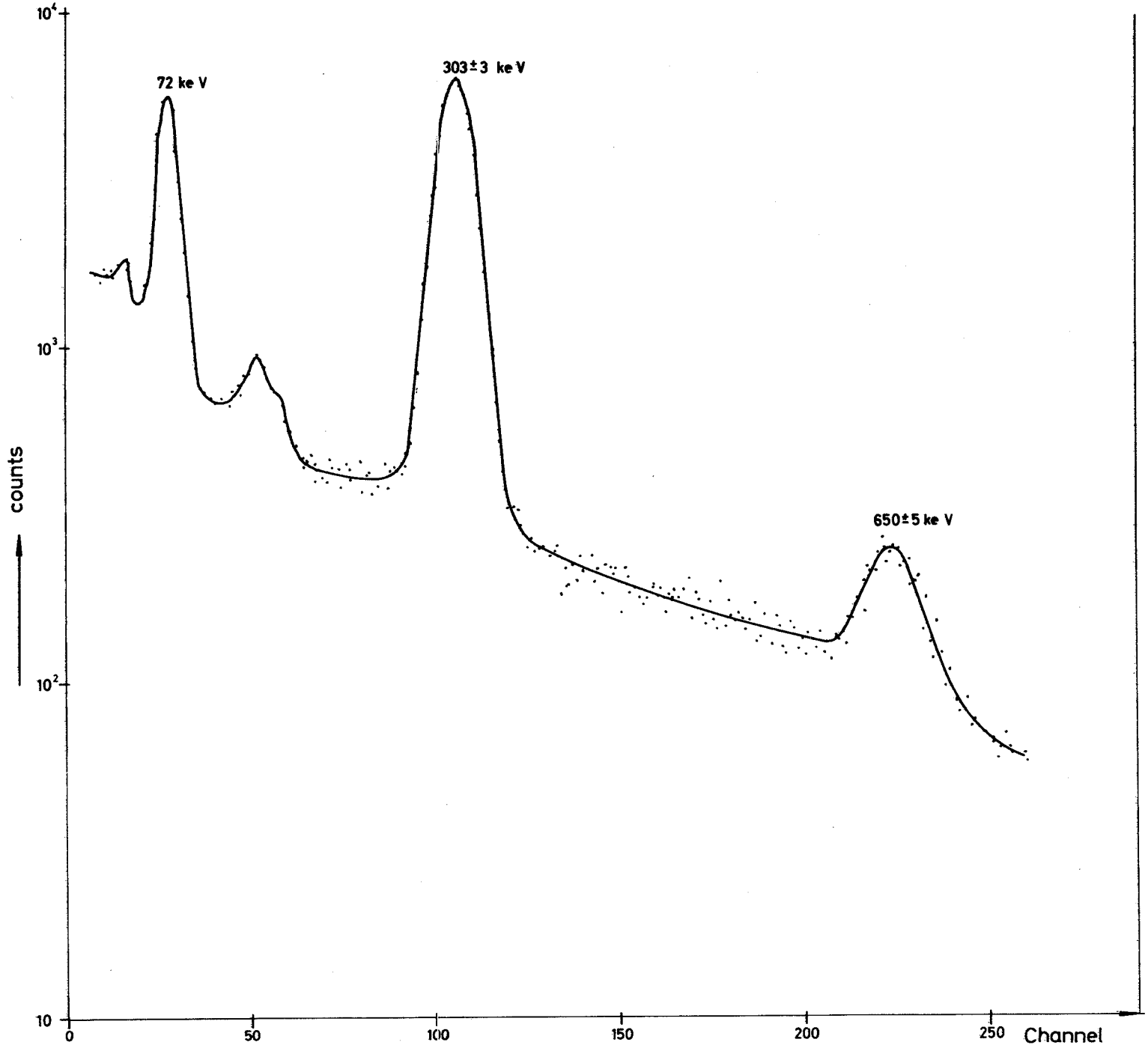
72 ke V
303±3 ke V
650±5 ke V
counts
10^4
10^3
10^2
10
0
50
100
150
200
250
Channel

Fig 2

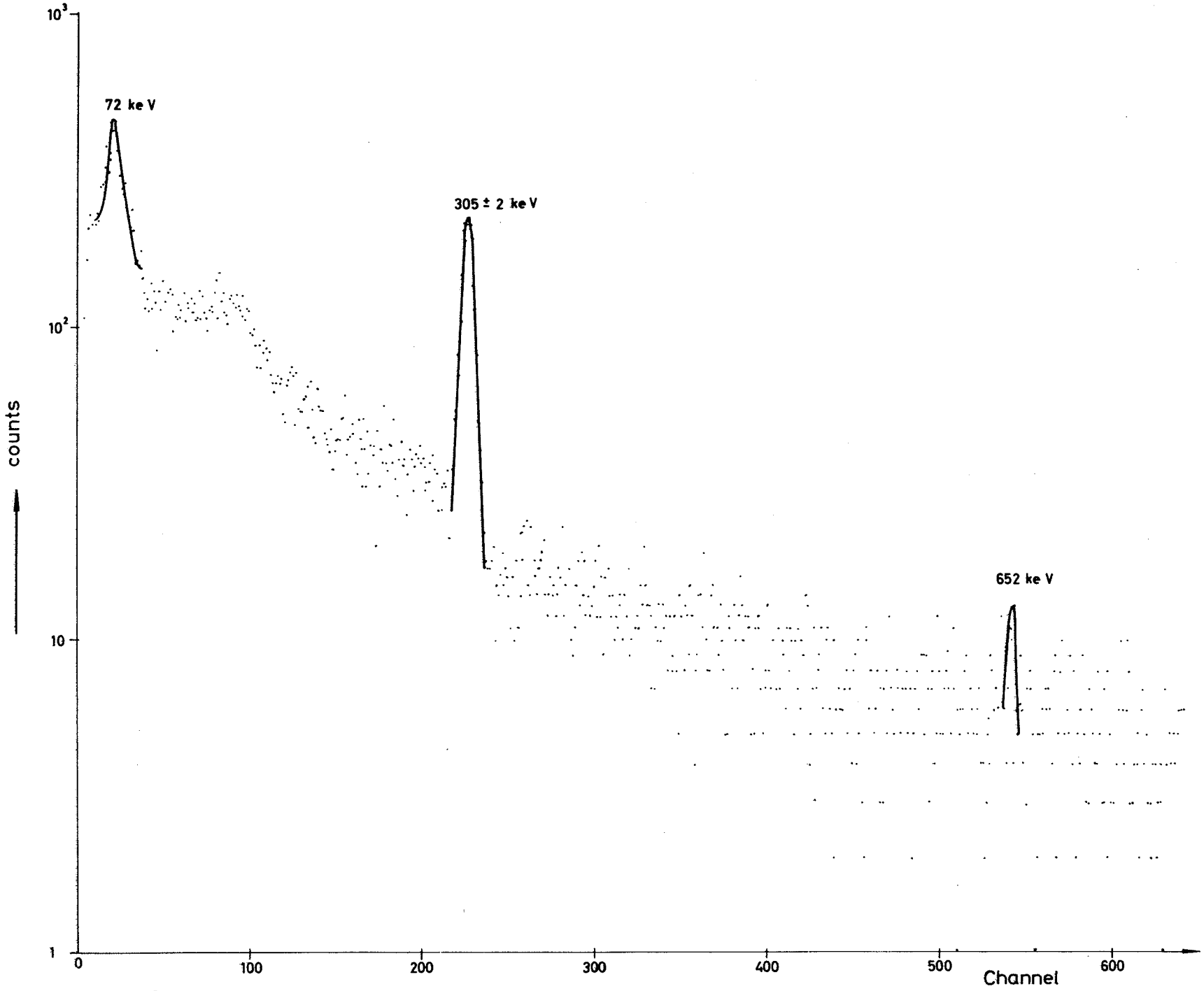
72 ke V
305 ± 2 ke V
652 ke V
counts
Channel
10^3
10^2
10
1
0
100
200
300
400
500
600

Fig 3

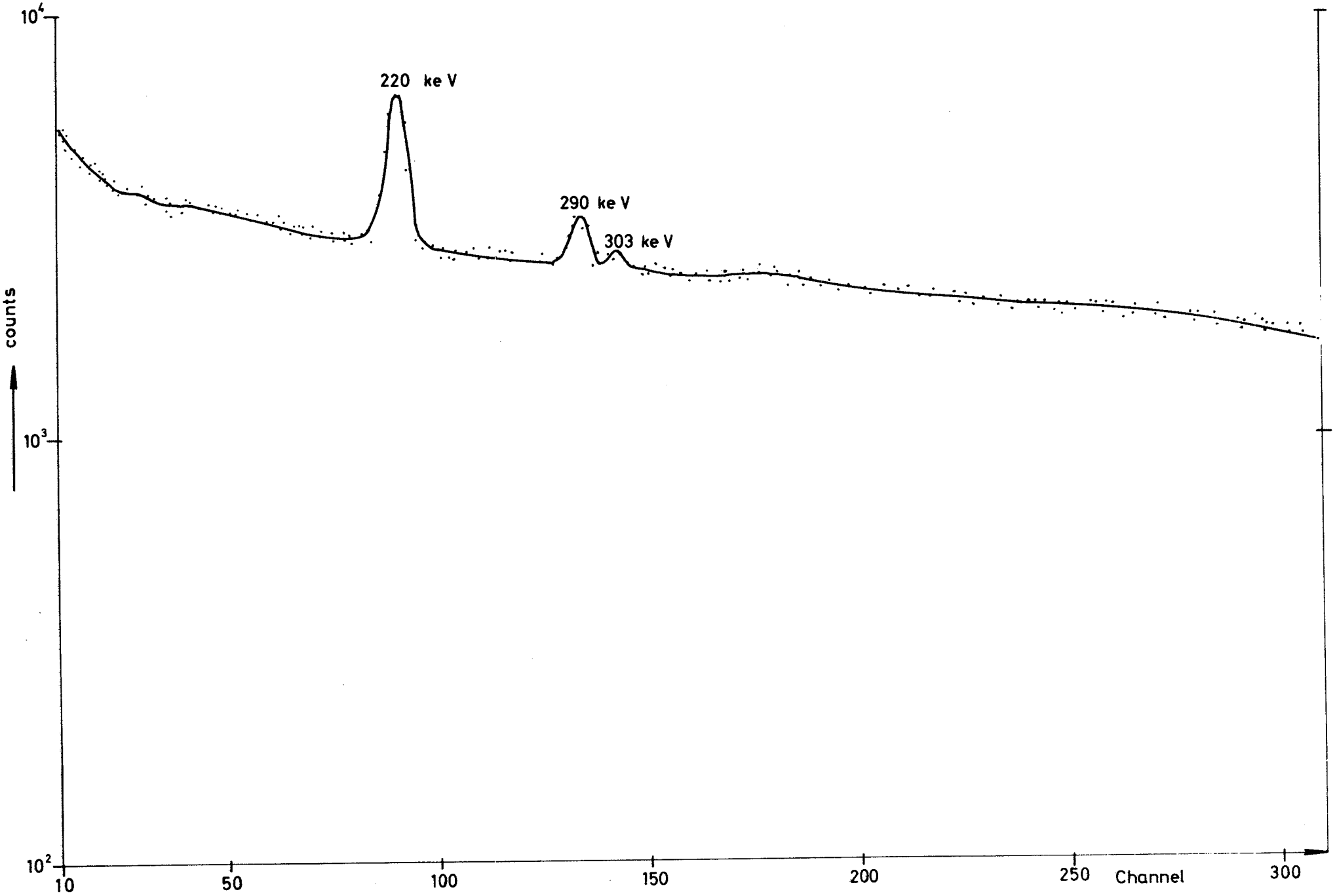
10^4
220 ke V
290 ke V
303 ke V
counts
10^3
10^2
10
50
100
150
200
250
Channel
300

Fig 4

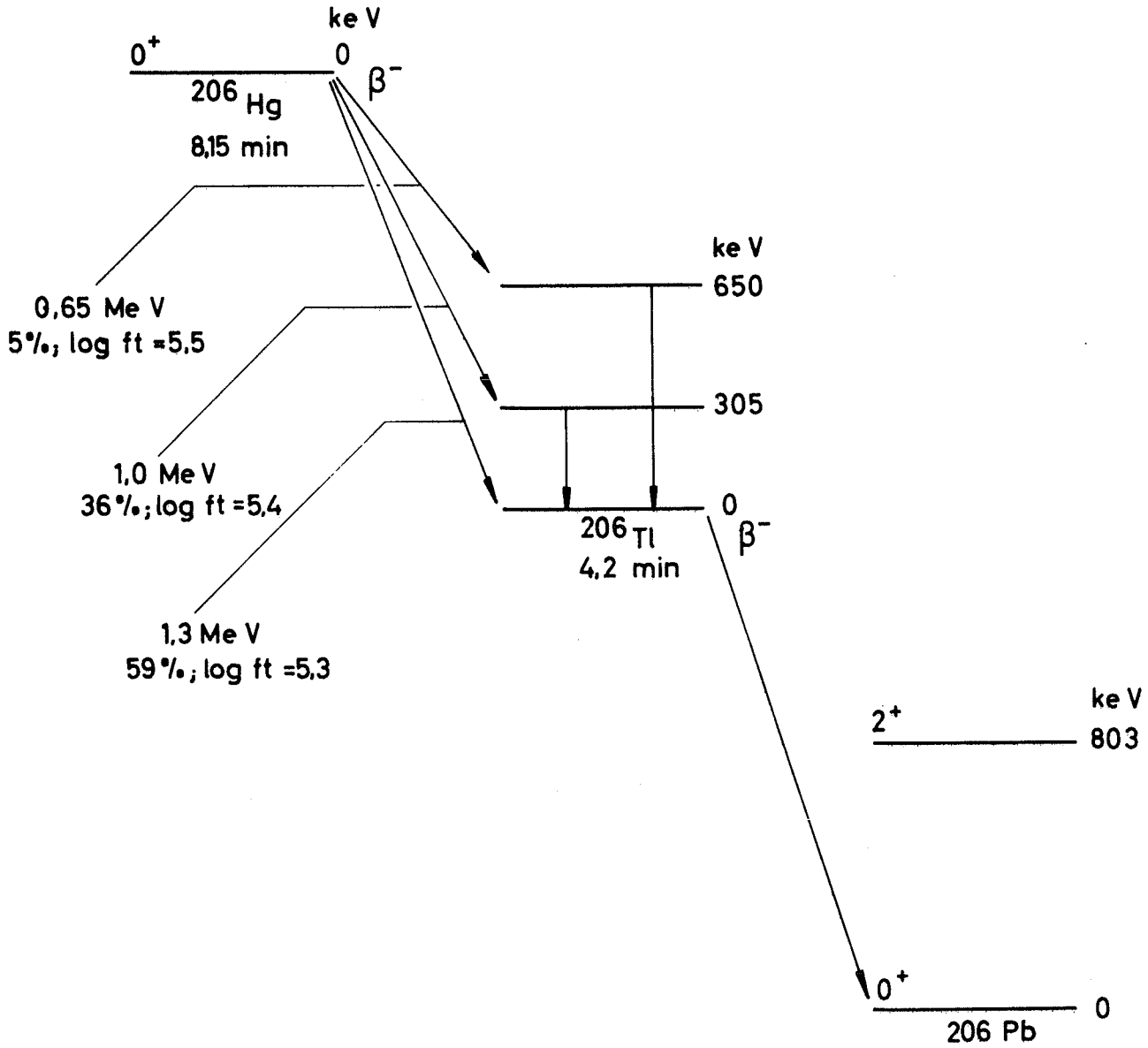
ke V
0+
0
β−
206 Hg
8,15 min
0,65 Me V
5%; log ft =5,5
1,0 Me V
36%; log ft =5,4
1,3 Me V
59%; log ft =5,3
ke V
650
305
0
206 Tl
4,2 min
β−
ke V
2+
803
0+
0
206 Pb

Fig 5

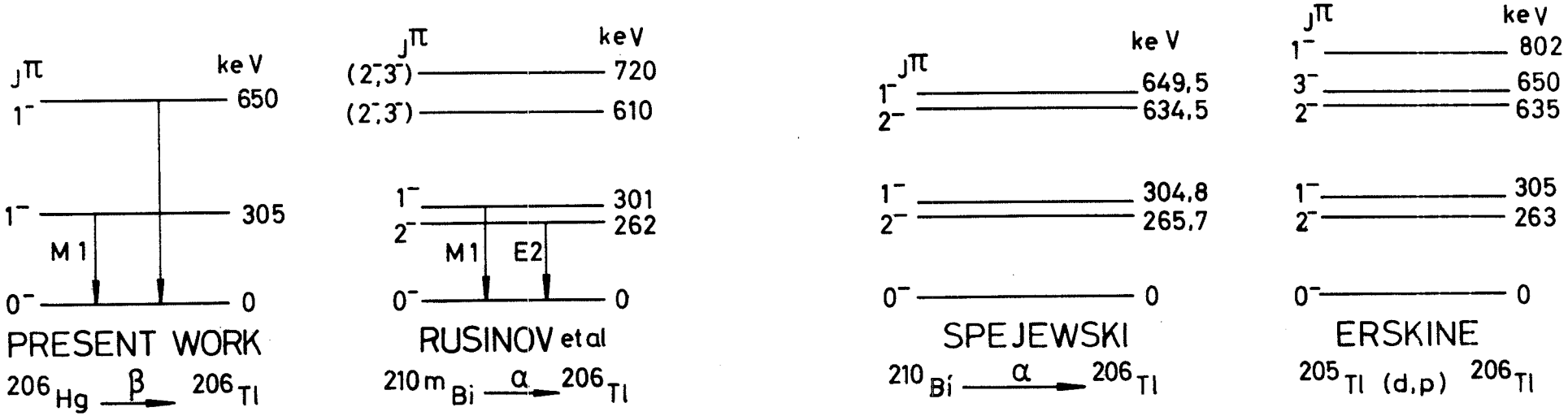
Jπ
keV
1⁻ 650
1⁻ 305
M1
0⁻ 0
PRESENT WORK
206Hg β 206Tl
Jπ
keV
(2⁻,3⁻) 720
(2⁻,3⁻) 610
1⁻ 301
2⁻ 262
M1 E2
0⁻ 0
RUSINOV et al
210m Bi α 206Tl
keV
Jπ
1⁻ 649,5
2⁻ 634,5
1⁻ 304,8
2⁻ 265,7
0⁻ 0
SPEJEWSKI
210Bi α 206Tl
Jπ
keV
1⁻ 802
3⁻ 650
2⁻ 635
1⁻ 305
2⁻ 263
0⁻ 0
ERSKINE
205Tl (d,p) 206Tl

Fig 6