NUCLEAR LIFETIME MEASUREMENTS
USING Pb-LOADED PLASTIC SCINTILLATORS

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Abstract

The half-lives of the 81 keV, 160.6 keV ; 384 keV and 437 keV levels in ^{133}Cs have been measured using the delayed coincidence techniques and Pb-loaded plastic scintillators. Analysis of the data gave the following half-life values :

$T_{\frac{1}{2}}$ (81 keV level) = 6.15 ± 0.08 ns

$T_{\frac{1}{2}}$ (160.6 keV level) ≦ 0.193 ns

$T_{\frac{1}{2}}$ (384 and/or 437 keV level) ≦ 0.36 ns

An explanation for the descripencies between the different results given by different authors is given. From the obtained results the experimental partial transition probabilities are calculated and compared with the single particle Weisskopf estimations.

1. Introduction

Lifetimes in the range 10^{-8} to 10^{-11} sec are usually measured by the time-to-pulse height converter techniques. The scintillation detectors have proved to be the fastest detector for such techniques.

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The rapidly increasing use of fast scintillation detectors has been greatly facilitated by the development of suitable fast luminescent materials. An important group among them are plastic scintillators (organic scintillators) either pure or in various combinations of solid solutions. These scintillators have the advantage of showing short decay time τ , while have the disadvantages of showing low total detection efficiency, zero photopeak detection efficiency and/or poor energy resolution as compared with the best inorganic scintillators such as NaI(Tl) crystals.

Only few trials[1-3] have been performed by various authors to combine the best properties of both organic (plastic) and inorganic (NaI(Tl) crystal) scintillators. However, these trials did not offer any clear and easy means of measurements and thus no practical applications of such trials have been reported.

Regarding our previous studies[4] on the properties of pure Naton 136 and some Pb-loaded plastic scintillators as well as NaI(Tl) crystals, it has been proved that as far as one is interested in performing a fast timing experimental analysis of low energy gamma-ray transitions with short decay time, high efficiency, high light output as well as relatively good energy resolution, the 2 % Pb-loaded plastic scintillator is better than all other mentioned scintillators.

The decay of ^{133}Ba to ^{133}Cs has recently attracted a certain amount of interest. The decay of ^{133}Ba has been studied by many authors[5-8] and the level scheme may be considered as well established. Although that the decay scheme is relatively simple, some discrepancies remain concerning lifetime measurements of levels and, therefore absolute transition probabilities. This is mainly due to the fact that most of the levels are populated and depopulated by gamma transitions having adjacent energies and thus difficult to be seperated by due to the poor energy resolution of fast scintillators. The half-lives of several levels in ^{133}Cs have been measure by several authors[9-16]. Some of their results agree while the others disagree.

In the present work, the improved properties of the 2 % Pb-loaded plastic scintillators are used to measure the half-lives of the 81 , 160.6 , 384 and/or 437 keV levels in ^{133}Cs. The obtained experimental results are compared with the theoretical single particle estimates.

2. Experimental Arrangements

2.1. SOURCES

The ^{133}Ba sources, used in the present investigation, were obtained from the radiochemical centre in Uppsala. These were made by evaporating commercially available activity onto 800 $\mu g/cm^2$ nickel foils.

2.2. APPARATUS

The experimental set-up used in the half-life measurements consists of an ORTEC model 437A fast time-to-pulse height converter and the energy selection channels. The gamma rays were detected by two scintillation detectors. Each detector consisted of a 2 % Pb-loaded plastic scintillator (25mm dia x 10 mm hight) coupled to an XP 2020 photomultiplier tube. The system is essentially a fast-slow coincidence system based on constant fraction timing spectrometry. The data were recorded on an Intertechnique 400 channel analyser. The system was calibrated with known lengths of well calibrated cables.

The system time resolution at low energy was determined with one of the two 2 % Pb-loaded plastic scintillators selected at 356 keV with a window width of ~ 50 keV on the stop channel and the other 2 % Pb-loaded plastic scintillator selected at 30 keV K X-ray with a window width of ~ 25 keV on the start channel using a ^{22}Na source and was found to have a slope ≃ 0.36 ns and FWHM ≃ 1.10 ns .

3. Measurements and Results

Fig. 1 shows a simplified level scheme[8] of ^{133}Cs . The gamma-ray spectrum of ^{133}Cs nucleus detected by 2 % Pb-loaded plastic scintillator coupled to an XP 2020 photomultiplier tube is shown in fig. 2 .

3. 1. The 81 keV Level

According to the decay scheme of ^{133}Cs nucleus fig. 1 , the gamma-rays populating the 81 keV level are the 356 , the 302 and the 79.6 keV transitions . It can also be seen (fig. 2) that owing to the improved properties of the 2 % Pb loaded plastic scintillators , the gamma line of the 81 keV is seperated in the gamma-ray spectrum of the ^{133}Cs nucleus detected by 2 % Pb-loaded plastic scintillator detector. Thus one has to measure delayed coincidences between the high energy part (above 250 keV) of the gamma-ray spectrum of ^{133}Cs (fig. 2) including the 302 keV and the 356 keV transitions populating this level selected in the start channel and the 81 keV gamma-ray transition depopulating this level selected in the stop channel. A certain admixture of almost prompt coincidences from other levels was registered. The delayed coincidence curve obtained with this adjustment had to be compared with a prompt coincidence curve, as shown in fig. 3 . This curve was measured with the aid of ^{22}Na source with the same channel adjustments. A least squares fit of an exponential function to the experimental data was made by means of a computer programme . Taking into consideration the statistical and systematic errors due to time calibration and electronic instability of the apparatus, the half-life of the 81 keV level was determined to be ,

$$T_{\frac{1}{2}} \text{ (81 keV level) } = \text{[illegible]} \pm 0.08 \text{ ns}$$

3. 2. The 160.5 keV Level

It is clear from the level scheme of ^{133}Cs (fig. 1) that this level is populated by the 223 keV and the 276 keV transitions and is depopulated by the 79.6 keV and the 160.6 keV transitions. Since both the 223 and 160.6 keV transitions are weak , the most probable coincidence combination is hence between the 276 keV transition populating this level adjusted in the start channel and the 79.6 keV transition depopulating this level adjusted in the stop channel. It seems also natural to measure the lifetime of the 160.6 keV level using the centroid shift method . Therefore, one of the timing single channel analysers was set to accept the 80 keV gamma-ray energy (with window of about 60-100 keV) the other timing single channel analyser was set to accept the 276 keV high gamma-ray energies from 250 keV to 300 keV. The time spectrum obtained with this adjustment , had to be compared with a prompt time coincidence spectrum. This prompt coincidence spectrum was measured with the aid of a ^{60}Co source with the same channel adjustments. The centroid shift between the delayed time coincidence spectrum of ^{133}Cs and the prompt time coincidence spectrum of ^{60}Co should be corrected for the contributions of the other admixed coincidences.

It is clear that the time distribution curve obtained is composed mainly from four contributions :

i) γ ($\geqq$ 250 keV) - γ (81 keV) coincidences belonging to a delay time equals to + τ_{81}

ii) γ (276 keV) - γ (79.6 keV) coincidences belonging to a delay time equals to + $\tau_{160.6}$.

iii) γ(276 keV) - γ (K X-ray) coincidences belonging to a delay time equals to - τ_{437} .

iv) γ (302 keV) - γ (53.4 keV)- K X-ray coincidences belonging to a delay time equals to - (τ_{384} + τ_{437}) .

The first contribution was found to be of the order of 5-7 % with a long lived decay time ($T_{\frac{1}{2}}$ of the 81 keV level $\simeq$ 6.15 ns). This was simply substracted from the time distribution curve . Each of the other contributions was calculated from the partial relative intensities of the contributing transitions listed in the nuclear table of isotopes[8].

Having applied these corrections a value for the half-life of the 160.6 keV level in ^{133}Cs was found to be ,

$$\tau_{160.6} = -2.953\ \tau_{total} + 1.238\ \tau_{437} + 0.715\ \tau_{384}$$

where τ_{total} is the observed mean lifetime. The value of τ_{total} was obtained after analyzing about 40000 coincidences in a large number of repeated short measurements and taking into consideration the statistical and instrumental errors due to time calibration and electronic instability of the apparatus, the average value for the centroid shift (mean lifetime) between the 276 keV gamma-rays and the 80 keV gamma-rays in ^{133}Cs and the prompt ^{60}Co curves was found to be ,

$$\tau_{total} = 29 \pm 11.5 \quad ps$$

If we take into consideration the values of the half-lives $T_{\frac{1}{2}}$ (384 keV level) = 40 $\pm$ 20 ps & 50 ps reported by Välivaara et al.[13] & Alkasov et al.[15] , respectively , and $T_{\frac{1}{2}}$ (437 keV level) $\leq$ 150 ps reported by Välivaara et al.[13] & Vartapetian et al.[16], our final result for the half-life time of the 160.6 keV level was found to be ,

$$T_{\frac{1}{2}}\ (160.6\ \text{keV level}) \leq 193 \quad ps$$

3. 3. The 384 KeV and 437 KeV Levels

As can be seen from the level scheme of ^{133}Cs presented in fig. 1 , the 384 keV level is directly populated by 22 % electron capture and depopulated by the 223 , 303 and 384 keV transitions of relative intensities 1 % , 65 % and 34 % respectively , while the 437 keV level is directly populated by 78 % electron capture and depopulated by the 53 , 276 and the 356 keV transitions of relative intensities 0.1 % , 9 % , and 91 % , respectively . Since the 53 keV and 223 keV transitions is very weak and either the 356 keV and the 384 keV transitions and/or the 276 keV and the 303 keV transitions depopulating these two levels cannot be resolved in the gamma spectrum, therefore, the most probable way is to measure delayed coincidences between the KX-ray adjusted in one channel and the high energy (above 300 keV) gamma spectrum of ^{133}Cs (fig. 4) including the 356 keV and the 384 keV transitions adjusted in the other channel . The delayed coincidence spectrum obtained with this adjustment, had to be compared with a prompt coincidence spectrum. This spectrum was measured using ^{22}Na source with the same channel adjustments. Since the observed time spectrum for the delayed coincidence has a slope which is equal to the instrumental slope of the prompt time resolution curve, recorded with the same energy settings, an upper limit for the half-life of either the 384 keV or the 437 keV levels was obtained :

$$T_{\frac{1}{2}} \text{ (384 keV or 437 keV level) } \leqq 0.36 \text{ ns}$$

4. Results and Discussion

The obtained value for the half-life of the 81 keV level ($T_{\frac{1}{2}}$ = 6.15 ± 0.08 ns) is in good agreement with all previous measurements . Concerning the half-life of the 160.6 keV level, it is clear that the value obtained by ref. 13 ~~8~~14 is nearly double the values reported by refs. 10, 11 and 12 . This disagreement could be explained by the fact that in the results given by refs. 10 and 11 , the effect of admixed coincidences were not taken into consideration . These admixed coincidences will affect the centroid of the measured time distribution curve and will decrease the value obtained for the half-life of the 160.6 keV level by a factor depending on the selected windows for each experimental conditions . The effect of these admixed coincidences on the results reported by ref. 13 and 14 is highly attenuated since the desired transitions are selected by a double lens β-spectrometer before measuring their time distribution.

Concerning the results obtained in the present work, unfortunately, the corrected value for the half-life of the 160.6 keV level will depend on the values of the half-lives of the 384 and 437 keV levels . If we take into considerations, the values given by refs. 13 , 15 , and 16 for these two levels, only a limit for the half-life of the 160.6 keV level could be reached ($T_{\frac{1}{2}} \leq$ 0.193 ns) . This limit is in agreement with all previous values[10–14].

An important conclusion could be deduced from this result . This conclusion is that, if the value ($T_{\frac{1}{2}}$ = 0.190 $\pm$ 0.015 ns) given by ref. 13 for the half-life of the 160.6 keV level is confirmed by other measurements , our results will give a value of $T_{\frac{1}{2}}$ = 0.150 ns instead of $T_{\frac{1}{2}} \leq$ 0.150 ns for the half-life of the 437 keV level .

From the experimental point of view, direct measurements of the half-life of the 437 keV level is rather difficult. This is mainly due to the fact that this level is populated and depopulated by gamma transitions whose energies differ slightly from other gamma transitions populating and depopulating the 384 keV level . This small energy difference is much smaller than the possible energy resolution of known fast scintillation detectors. Therefore, the trial done in the present work to measure the half-life of the 437 keV level will lead only to a limit value. This limit value should be only considered as an indication for the capability of Pb-loaded plastic scintillators to measure half-lives of low energy gamma transitions. It is worthwhile to mention that the present measurement proves the possibility of performing fast time distribution measurements for X- or γ-rays in the energy range of 30 keV using Pb-loaded plastic scintillators. This possibility could not be reached using the common pure plastic scintillators owing to the fact that only Compton interaction is possible in such type of pure plastic scintillators (E_{max} Compton for the 30 keV $\approx$ 3 keV).

The results of our experimental measurements for the half-lives have been collected in table I together with the transition energies, relative gamma-ray intensities, multipole mixing ratios, branching ratios and theoretical internal conversion coefficients collected from other published data[6,19]. These data have been used to calculate the partial gamma-ray half-lives $T^{exp}_{\frac{1}{2}\gamma}$ for all transitions, according to

$$T^{exp}_{\frac{1}{2}\gamma} = \frac{t_{\frac{1}{2}}(1+\alpha)}{X}$$

where α is the total internal conversion coefficient found by interpolation from the tables of Sliv and Band[19), and X is the branching ratio extracted from experimental published data.

From the partial half-lives, the experimental partial transition probabilities were deduced and compared with the theoretical single-particle Weisskopf estimates[20]. To obtain the Weisskopf estimates a nuclear radius constant of 1.2 fm and a statistical factor S = 1 were used[20].

From the theoretical single-particle Weisskopf estimate of the partial transition probabilities $B_{\gamma}^{Weisskopf}(M1 \text{ or } E2)$ and the experimental partial gamma-ray transition probabilities B_{γ}^{exp}, the retardation and enhancement factors can be evaluated by employing the mixing ratios δ. The retardation and enhancement factors for the M1 and E2 transitions, respectively, are given by :

$$R(M1) = \frac{B_{\gamma}^{Weisskopf}(M1)}{B_{\gamma}^{Exp}}$$

$$B(E2) = \frac{B_{\gamma}^{Exp}}{B_{\gamma}^{Weisskopf}(E2)}$$

Table I also shows the calculated retardation and enhancement factors. According to the present values of the above mentioned parameters in this table, the lower limits of the enhancement factors for the 356 keV and 276 keV transitions which are of pure E2 multipolarity and depopulating the 437 keV level support the Weisskopf predictions for the partial transition probabilities of a single proton. The large enhancement factor obtained for the 53 keV transition depopulating the same level gives us an indication of the existence of collective effects.

The lower, limits of the enhancement factors for the 384 keV transition of pure E2 multipolarity depopulating the 384 keV level support also the Weisskopf single particle predictions for the partial transition probability of a single proton. The M1 part of the 303 keV transition depopulating the 384 keV level is strongly retarded while the lower limit of the E2 part is enhanced by about the same amount below the single particle estimation, indicating that the E2 part of this transition is somewhat better accounted for in the single particle estimates.

References

1) De Boer, Th. J., S. S. Klein, E. W. Ten Napel, J. Blok, Nucl. Instr. & Meth. 21 (1963) 347 .

2) Vergnes, M., R. David-Boyer : J. de Phys. et Rad. 21 (1960) 65 .

3) Abou-Leila, H. : Doctorat es sciences Thesis, Paris 1967 .

4) Abou-Leila, H., S. M. Darwish, A. A. El Kamhawy, H. A. Ismail and S. M. El Bahi : Atomkernenergie Bd. 28 (1976) Lfg. 2 , 131 .

5) Thun, J. E., S. Törnkvist, K. Bonde Nielsen, H. Snellman, F. Falk and A. Mocoroa : Nucl. Phys. 88 (1966) 289 .

6) Notea, A. and Y. Gurfinkel : Nucl. Phys. A 107 (1968) 193 .

7) Bosch, H. E., A. J. Haverfield, E. Szichman and S. M. Abecasis : Nucl. Phys. A 108 (1968) 209 .

8) Lederer, C. M., J. M. Hollander and I. Perlman, Table of Isotopes (J. Wiley & Sons, New York, 1967).

9) Bondenstedt, E., H. J. Körner and E. Matthias, Nucl. Phys. 11 (1959) 584 .

10) Flauger, W., and H. Schneider : Atomkernenergie 8 (1963) 453 .

11) Scharbert, T., Acta Phys. Hung. Tom. 20 (1966) 185 .

12) Imanishi, N., F. Fukuzawa and M. Sakisaka, Nucl. Phys. A 101 (1967) 654 .

13) Välivaara, K. G., A. Marelius and J. Kozyczkowski, Physica Scripta 2 (1970) 19 .

14) Badawy, O. E., Z. Awwad, M. R. El Aassar and A. El-Farrash : Atomkernenergie 19 (1972) 58 .

15) Alkasov, D. G., K. I. Erokina and I. K. Lemberg, Izv. Akad. Nauk. SSSR, ser fiz. 28 (1964) 1667 .

16) Vartapetian, H. A., A. G. Khudaverdia and T. A. Garibian, Compt. Rend. Congres Int. de Phys. Nucl. 2 (1964) 520 .

17) Bond, P. D., J. D. McGervey and S. Jha, Nucl. Phys. A 163 (1971) 571 .

18) Gupta, D. K. and G. N. Rao, Nucl. Phys. A 182 (1972) 669 .

19) Sliv, L. A. and I. M. Band, α-, β - and γ-Spectroscopy ed. by K. Siegbahn (North-Holland Publ. Company, Amesterdam, (1965) App. 5) .

20) Moszkowski, S. A., α -, β - and γ -Spectroscopy, ed. by K. Siegbahn (N.-H. Publ. Co., Amesterdam, 1965, p. 881) .

Tablo I

The retardation and enhancement factors for M1 and E2 transitions in ^{133}Cs

Level (keV)	Half-life (ns)	E_γ a) (keV)	I_γ a) %	Multi-polarity	Branch ratio b) X	Mixture ratio b) δ^2	I. C. C. α c) M1	E2	R (M1)	E (
81	6.15±0.08	81	100	M1 + E2	1.0	0.0240	1.45	2.30	366± 5	4.6 ±
160.6	≦ 0.193	160.6	12	M1 + E2	0.118	0.3480	0.22	0.28	≦ 501.0	≧ 15
		79.6	88	M1 + E2	0.882	< 0.0625	1.53	2.40	≦ 13.5	≧ 333
384	≦ 0.360	384	34	pure E2	0.313	—	—	0.018	—	≧ 1
		303	65	M1 + E2	0.6682	≦ 0.0144	0.036	0.035	≦ 703.0	≧ 0
		223	1	M1 + E2	0.0189		0.11	0.10	—	—
437	≦ 0.360	356	91	pure E2	0.741	—	—	0.021	—	≧ 4
		276	9	pure E2	0.0889	—	—	0.047	—	≧ 2
		53	0.1	M1 + E2	0.170	≦ 0.1160	4.9	6.8	≦ 92.7	≧ 207

a) Ref. 8 b) Ref. 6 c) Ref. 19

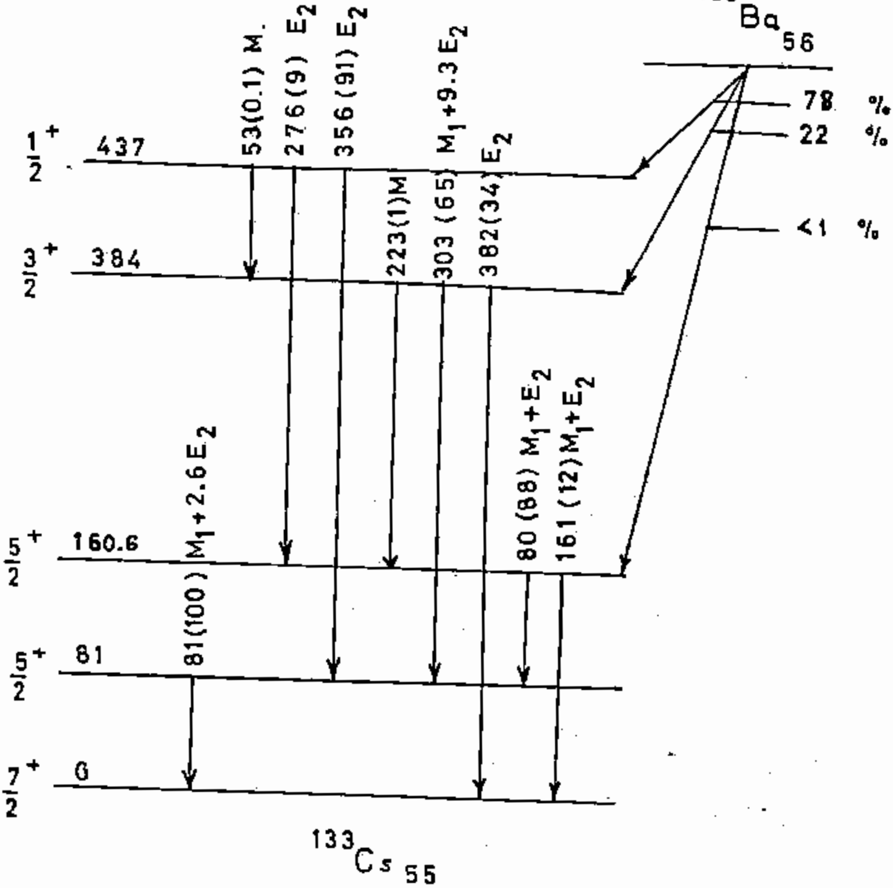
Figure Captions

Fig. 1 : A simplified level scheme of ^{133}Cs (Ref. 6) .

Fig. 2 : Direct gamma-ray spectrum of ^{133}Cs nucleus detected by 2 % Pb-loaded plastic scintillator coupled to an XP 2020 photomultiplier tube.

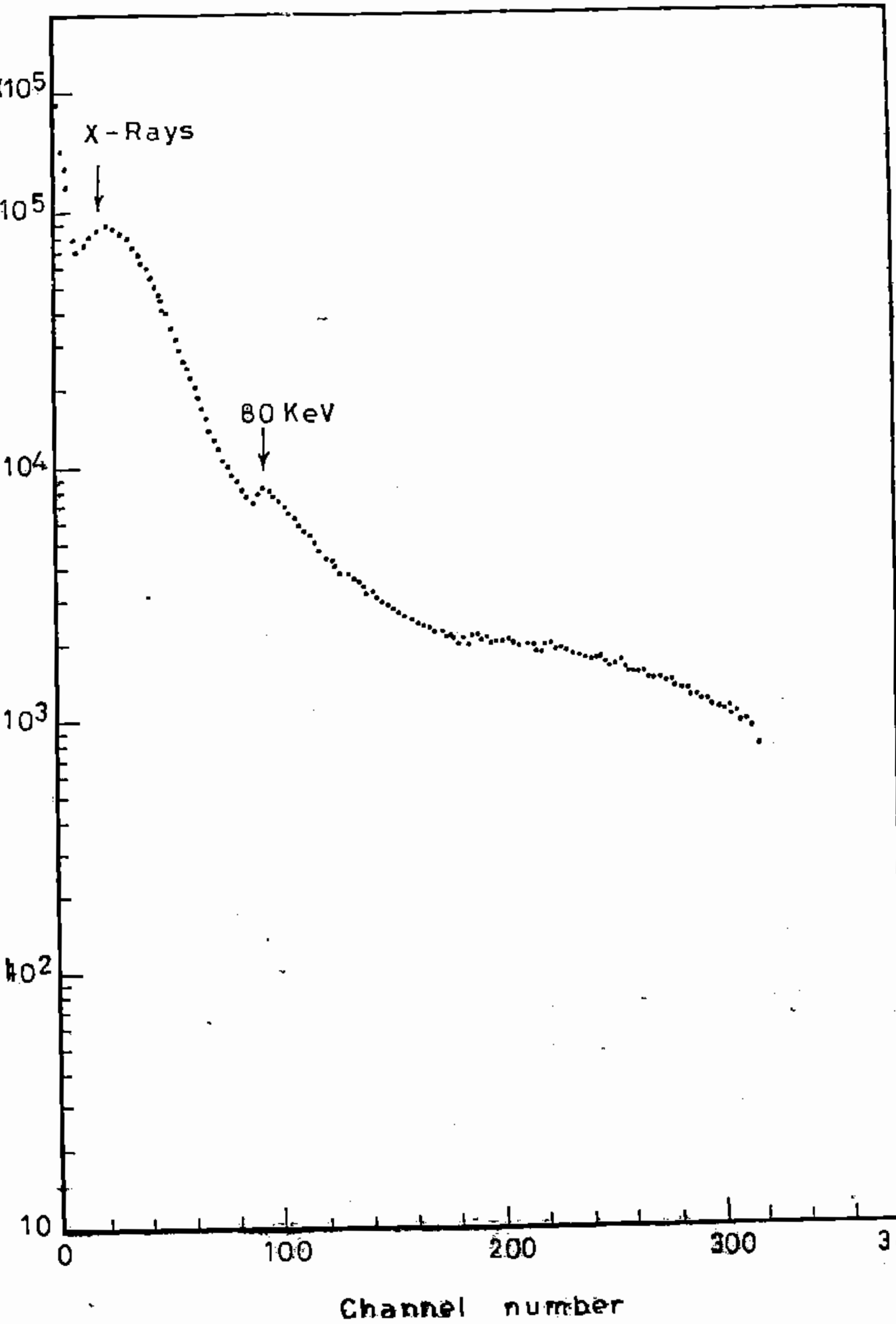
Fig. 3 (a)Time distribution curve for evaluation of the half-life of the 81 keV level.(b) Prompt

Fig. 4 (a)Time distribution curve for evaluation of the 384 and / or 437 keV levels .(b) Prompt

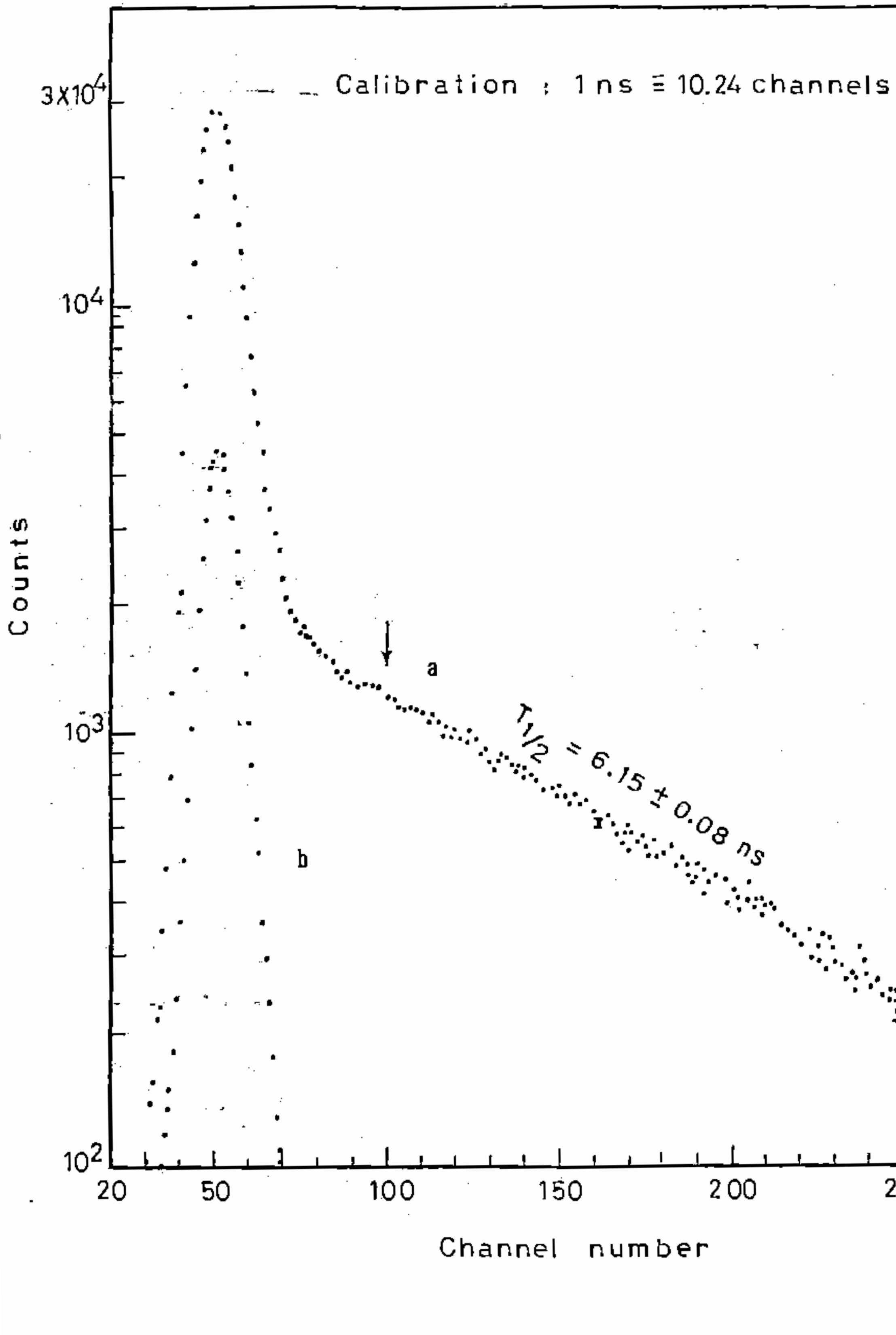


133 Ba 56
78 %
22 %
<1 %
1/2 + 437
3/2 + 384
5/2 + 160.6
5/2 + 81
7/2 + 0
53(0.1) M.
276 (9) E2
356 (91) E2
M1 +9.3 E2
E2
223(1)M
303 (65)
382(34)
M1+2.6 E2
81(100)
80 (88) M1+E2
161 (12) M1+E2
133 Cs 55

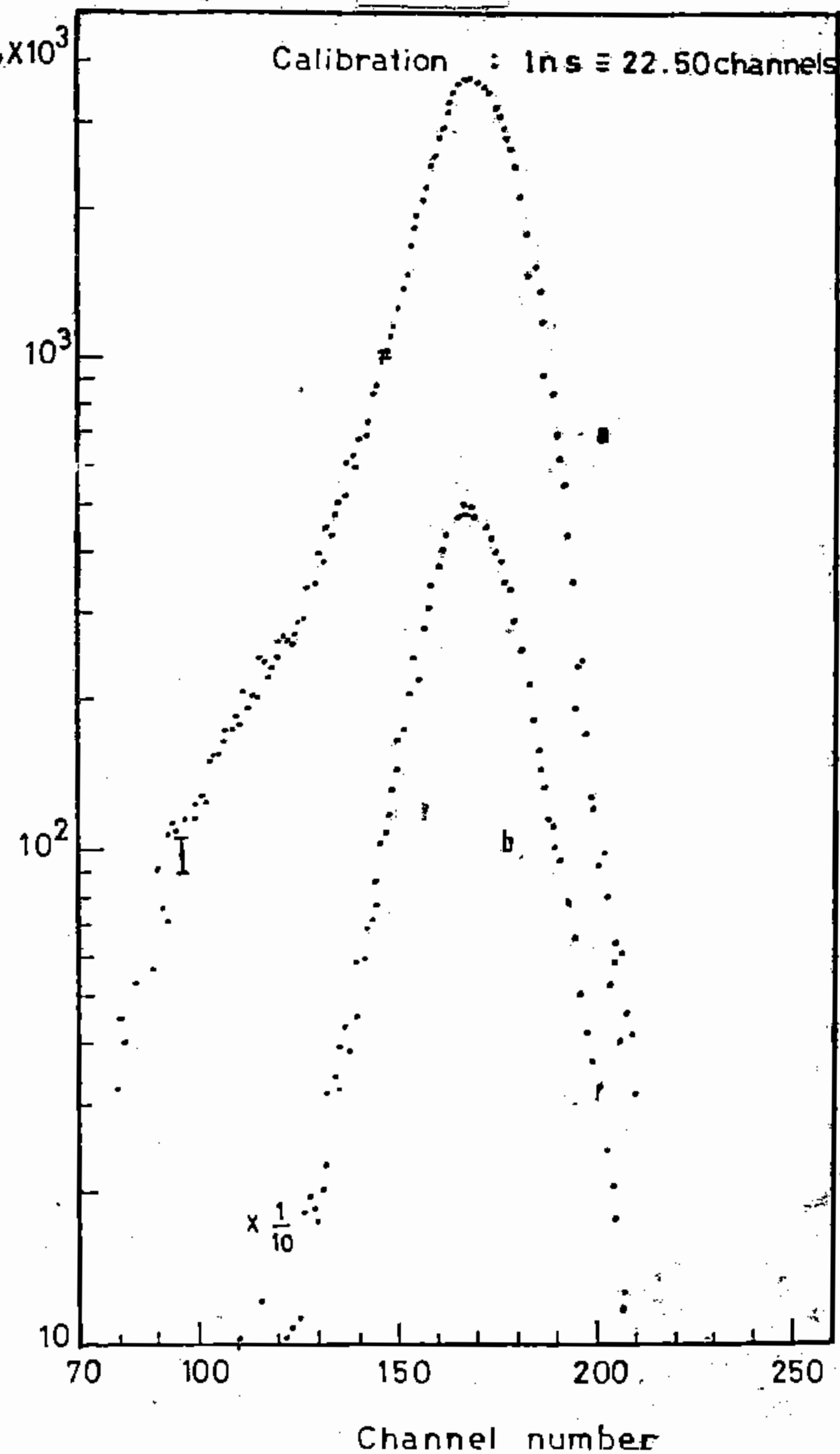
Fig ①



X-Rays
80 KeV
10^5
10^4
10^3
10^2
10
0
100
200
300
Channel number



Calibration : 1 ns ≡ 10.24 channels
3X10^4
10^4
10^3
10^2
Counts
a
b
T1/2 = 6.15 ± 0.08 ns
20
50
100
150
200
Channel number


X10³
Calibration : 1ns ≡ 22.50channels
10³
10²
10
a
b
x 1/10
70
100
150
200
250
Channel number