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Pulsed Neutron Experiments on FCA V-1

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Contents

Pulsed Neutron Experiments on FCA V-1*

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A b s t r a c t

Pulsed neutron experiments have been performed on FCA V-1, the physics mockup core for the JOYO.

Neutron decay curves have been measured at several different reactivities from the delayed critical down to -6$. In all cases, single exponential decays are observed after the constant delayed component being subtracted.

Prompt neutron decay constant α and the reactivity ρ_p in doller unit are determined for each decay curve.

Both α's and ρ'_{ps} show no dependence on detector positions or energy responses in the measured reactivity range (down to -2$).

α and ρ_p hold good linear relation down to -6$.

The prompt neutron decay constant at delayed critical, α_c is determined as $0.341 \pm 0.031 \times 10^5$ sec^{-1}.

α_c calculated by SNKPARAM with JAERI-FAST set is about 13% larger than the experimental value.

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* Work performed under contracts between Power Reactor and Nuclear Fuel Development Corporation and Japan Atomic Energy Research Institute (JAERI).

** JAERI.

I Summary

A series of pulsed neutron experiments have been carried out on FCA V-1[1]. The purposes of these experiments were (1) to obtain the value of the prompt neutron decay constant at delayed critical αc ($= \frac{\beta eff}{\ell_p}$) as one of the important physical quantities in the physics mockup for the Experimental Fast Reactor "JOYO" and (2) to see if there were any differences from the pulsed neutron experiments performed by FCA on the reactor core of the uranium system in the techniques and results.

The pulsed neutron experiments have hitherto been made systematically on several kinds of uranium cores and the single exponential decay was observed with a sufficient degree of accuracy within the range of several dollers, thus showing that the analysis by a simple one-point reactor model is effective.[2][3][4]

Since the mockup core V-1 contains a considerable amount of plutonium fuel, it differs from the previous uranium system in that there are the effects of the background neutron sources due to the spontaneous fission of plutonium isotopes and the value of βeff varies largely.

So, in the present experiments, we check the applicability of the pulse method, which was developed with the uranium system so far, to the plutonium system to see what would become in the plutonium system of the properties and relations of the decay constant α and the reactivity ρ_p in the doller unit measured by the pulse method and the differences between the experimental and calculated values.

However, with regard to the second purpose, we did not perform such comprehensive experiments that the detector position is changed systematically or a parallel comparison is made of those with different

energy responses for the reasons of the machine time of FCA and the reactivity was varied in a rather narrow range. Only the necessary and minimum experiments were made as the first step in the transition to the plutonium system.

II Experimental System and Method

1. Core

The composition and geometry of the core which was used in the present experiments are shown in Table 1 and Fig. 1. This system is a version (V-1-D) of the V-1 core for the experiments. Since the target for generating neutrons is positioned near the center of the core, the five fuel drawers 18 - 13 through 18 - 17 on the fixed side are lowered by one pack (50.8mm) in the axial direction so that the beam extension tube may be inserted. (Since the fuel drawers are displaced by one pack without drawing out, this part of the core and the rear end of the blanket are so shaped as to protrude.) Since the experiments are also made at critical, seven half drawers are added to the periphery of the core in order to compensate the shift of fuel and the worth of the extension tube.

2. Detector

We used three fission counter tubes for the detectors. U-235 micro F.C.* (20th Century FC4/1000 : Det. 1) was set near the center of the core, in the sleeve of the experimenting hole in the first row on the F18 - 18 drawer and the medium-size N_p-237 F.C. (20th Century FC 165/300: Det. 2) and the high-sensitivity U-235 F.C. (R.S. 10A : Det. 3) were placed near the boundary of the core, in the matrix on F side as close to the midplane as possible.

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* Fission chamber

Det. 1 and Det. 3 are used for making measurements near critical and at highly subcritical and for checking the dependence on detector positions in the intermediate region. Since the target is approximately in the center of the core, Det. 2 is the same relative position with Det. 3 and is used for making comparison of detectors of different energy responses.

3. Circuit System

The same circuit system as in the case of the uranium system was used for the convenience of comparison with the previously obtained data. The time analyzer was composed of TMC 256 Ch. MCPA and TMC 201,211TOF plug-in units.

4. Measurement of Time Origin

Time origin is a quantity that is important in determining the reactivity by the pulse method.

In the present experiments, the detector was positioned closed to the target so that 14MeV neutrons were directly observed in order to determine the time origin. In order to avoid the unwanted multiplication, the fuel drawers in the three rows and the three columns near the target were removed on the fixed side and the measurements were made with the table separated. In order to accurately calculate the position of the origin, not only the combination of the pulse and the channel width which are used in actual measurements, but also the combinations in the vicinity, too, were systematically checked.

5. Variations in Reactivity

In order to vary the reactivity, after making critical adjustment by C/R#2, C/R#2 was moved and C/R#1 and S/Rs were fully withdrawn one by

one. Since this was not enough for the highly subcritical state, widening the gap between the two 1/2 assemblies was used. For the sake of comparison, we performed experiments at one point in such a manner that the reactivity became roughly the same by the control rod moving method and the table gap method.

6. Measurements at Delayed Critical

This is a method in which the value of α_c is obtained directly by driving the neutron pulse into the delayed critical system. First, all C/R and S/R, except C/R#2, are fully inserted and the critical point is determined (at 0.5×10^{-6} in Ch. 6) by C/R#2. With C/R#2 remaining in the same position, other C/R and S/R are withdrawn scores of millimeters so that the system may be below the critical state and the neutron level be lowered sufficiently to eliminate the effects of the delayed neutrons produced by the operation of the reactor up to that time. Now, C/R and S/R are fully inserted and at the same time the pulser of the pulsed neutron generator is set to "ON" and the beam shutter is opened to start making measurements. Since the component due to the delayed neutrons increases rapidly with the lapse of time, the measurement was continued only for 100 seconds at one time. This process was repeated several times to get reasonable statistics.

7. Measurements at Subcritical State

Measurements are made when the delayed component becomes steady after pulses have been driven repeatedly into the subcritical system. Since not only α but also ρ_p is obtained in this case, it is necessary to precisely know the component arising due to the delayed neutrons. For this purpose, it is necessary to eliminate the leak component (L)

of the beam which inevitably is mixed in the measurements and the background component (S) resulting from the spontaneous fission of a higher isotopes of plutonium. So, following this measurement, a similar measurement was carried out with the pulser of the neutron generator in its "OFF" position. In this case the measurement was made of the above two components combined and thus obtained value was subtracted from the measured total so that the time variation in the count was due solely to the pulse.

In actuality, there is no need to separate these two components but for the sake of checking a similar measurement was made with the beam shutter being closed to obtain S alone. The result was L : S = 0.44 : 0.56, showing that a little more than the half of the background count was due to the spontaneous fission of plutonium.

The signals from the pulse pickup were counted during the measurement in order to make several measurements of the repetitive frequency (F) of the pulse.

III Experimental Results and Analysis

The typical examples of the observed time spectra are shown in Fig. 2, Fig. 3 and Fig. 4. These spectra respectively correspond to the delayed critical, two C/Rs fully withdrawn (-0.9$) and C/Rs and S/Rs fully withdrawn +10mm gap (-6.2$). Since some higher-order component is contained near the time origin and particularly the detector is located close to the target in Fig. 4, there appeared the direct neutron pulse peak. However, in all cases, when the steady background component is subtracted, a single exponential decay was observed from near the origin.

Each decay curve was fitted to

$$A_o e^{-\alpha (t-t_o)} + B \qquad \cdots\cdots\cdots\cdots\cdots\cdots (1)$$

to obtain the decay constant α, the initial value of the fundamental mode Ao and the background B. Since the initial part was influenced by the higher-order modes and the uncertainty of the dead time compensation, the channel from which the fitting was started was shifted one by one and took the values of good statistics within the range in which the respective values were stabilized.

The reactivity ρ_p can be obtained by a simple one point model

$$-\rho_p = \frac{\rho}{\beta} = \frac{F}{Nd} \int_{to}^{\infty} n_p(t)\, dt \qquad \cdots\cdots\cdots\cdots\cdots\cdots (2)$$

F: pulse repetitive frequency

Nd: total count rate of delayed component

$_p(t)$: count rate of prompt component

As shown above, the higher-order components are slight so that they can be expressed mostly by a single exponential, therefore, the equation (2) can be rewritten as

$$\rho_p = \left(\frac{Ao}{\alpha}\right) \Big/ \frac{Nd}{F} \qquad \cdots\cdots\cdots\cdots\cdots\cdots (3)$$

$$Nd = B - (L + S) \qquad \cdots\cdots\cdots\cdots\cdots\cdots (4)$$

The reactivity can be obtained by substituting the already measured values of Ao, α, B, L + S, and F.

The results obtained by this method and the experimental conditions for the delayed critical and subcritical states are given in Table 2.

1. Decay Constant α

As seen from Table 2, the value of α can be obtained with an accuracy of 1 to 2%. The value was constant down to -2.2$ for the same core pattern regardless of the position and kind of the detector. It

was unknown for further down because we used only one kind of detector to make measurements but the α itself was obtained with an accuracy of less than 1%.

2. Reactivity ρ_p

The values of ρ_p were obtained with an accuracy of 2 to 3%. The importance of the assessment of t_o and L in the measurement of ρ_p was mentioned in Ref. 3. Here the uncertainty of t_o and L + S is not taken into count in the assessment of this error. The problem of t_o and L + S will be discussed later. In this case, too, there was fairly good agreement for the same patterns but there were some disagreements exceeding the errors.

3. Relationship between Decay Constant α and Reactivity ρ_p

The relationship between α and ρ_p is shown in Fig. 5 and Fig. 6. Fig. 5 shows the data for the entire range of measurements and Fig. 6 magnifies the data below -2$. From these data, it is seen that α and ρ_p hold good linear relation down to -2$ and relatively good down to -6$.

4. The Value of Decay Constant α_c at Delayed Critical

As seen in the preceding paragraph 3, the data down to -2$ are so well on a straight line. Therefore, from the value obtained by fitting the data to $\alpha = a\ \rho_p + b$ by using the least squares method, it is possible to get the extrapolated value for the delayed critical.

The results were

$$a = 0.326 \qquad b = 0.345 \pm 0.012$$

These values agree with the directly measured values within the range of errors.

This being so, as to the experimental value of α_c, the two data at critical and the exrtapolated value from the subcritical are equal weight averaged and the following value was obtained.

$$\alpha_c \text{ (E x p)} = (0.341 \pm 0.013) \times 10^5 \text{ sec}^{-1}$$

The point where the above straight line crosses the horizontal axis becomes $1.06\,\beta$. However, since there are errors for both a and b, it is unknown whether it is deviated from 1 or not.

5. Comparison with the Calculated Value of α_c

We calculated ℓ_p, β_{eff}, α_c of the core FCA V-1 on the JAERI-FAST 25-group set by use of SNKPARAM code.(5)

SN calculation was made with N=4 and Σ_{tr} was used for input Σ_t. The input data immediately relating to the calculation of ℓ_p, β_{eff} are shown below.

i) The average velocity of each group was the same as that used in the previous calculations by ABBN (KPARAM-2).

ii) β_i were all prepared from Keepin's(6) fast fission data*. As to P_u^{241}, the value of thermal fission was used because there were no fast fission data available for this.

iii) χ_d was the same as that used in KPARAM-2, that is, Kvitek's(7) χ_d for ANL 16-group was proportionally allotted by Δ_u of the 25 groups of ABBN.(8)

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* Comparison of β of various nuclides contained KPARAM-2 is shown below for the sake of reference.

$\beta \times 10^3$	^{239}Pu	^{240}Pu	^{241}Pu	^{235}U	^{238}U
KPARAM-2	2.103	2.667	5.337	6.420	15.701
Keepin	2.04	2.66	4.9 (thermal)	6.41	14.8

The results of calculation are as follows.

$$\ell_p = 1.42_3 \times 10^{-7} \text{ sec}$$

$$\beta_{eff} = 5.50_7 \times 10^{-3}$$

β_i values of nuclides are shown in Table 3.

Therefore $\alpha_c = \frac{\beta eff}{\ell_p}$ becomes $3.87_0 \times 10^4 \text{ sec}^{-1}$

The results of diffusion calculation[9] with ABBN set and KPARAM-2 code are

$$\ell_p = 1.30_0 \times 10^{-7} \text{ sec}$$
$$\beta eff = 5.63_1 \times 10^{-3}$$
$$\alpha_c = 4.33_2 \times 10^4 \text{ sec}^{-1}$$

From the above, the ratio of calculated values to experimental values becomes as follows.

$$\frac{\alpha_c(ca\ell)}{\alpha_c(exp)} = 1.13 \qquad \text{J.F - SNKPARAM}$$

$$= 1.27 \qquad \text{ABBN - KPARAM}$$

Table 4 shows the comparison of the values of $\alpha_c\ (_{ca}\ell)/\alpha_c\ (exp)$[4] on two types of uranium core which are similar to V-1. It is clearly seen that the degree of difference is very much alike the uranium system.

IV Review

The uncertainty of the measurements of reactivity is possibly due to i) the effective time origin t_o, ii) the steady neutron source (L + S), and iii) pulse repetitive frequency F.

i) Assessment of t_o

t_o can be obtained approximately by the following equation from the time distribution of pulse S (t).

$$to = \int_o^w t' S(t') dt' / \int_o^w S(t') dt' \quad \cdots\cdots\cdots\cdots (5)$$

However, since the measurements are not made continuously but discretely by a definite channel width T, the following equation may be used.

$$to = \sum_i i\, Si / \sum_i Si \quad \cdots\cdots\cdots\cdots (6)$$

In this case, however, when the pulse width is not large compared with the channel width, the error will be so large as maximum $\pm$ T/2.

In order to check the degree of effectiveness of the equation (6), we checked the variation in the effective t_o by performing experiments in which the channel width was made constant and the pulse width was varied in the measurements of the origin. Looking at a typical case in which the channel width was 0.25 μs and the pulse width 1 μs, 0.5 μs, and 0.25 μs, t_o by the equation (6) becomes 30.39ch, 29.36ch and 28.85ch and the time differences from the first were 1.03ch = 0.26 μs and 1.54ch = 0.39 μs. On the other hand, from the plotting of the origin time spectrum, the rise-up, that is, leading edges were all in agreement. This is a natural result if the discrimination level of the pulse from the pickup ring is correctly set and the height of pulse does not vary greatly due to the changes in the pulse width. This being so, if the pulse width is represented accurately, the time difference becomes 0.25 μs and 0.375 μs, which are well in agreement.

We also made a check on several cases in which different channel widths and pulse widths were combined and found that it was within the range of $\pm$10% against nominal variations. This shows that when the pulse width is equal or larger than the channel width, t_o can be assessed sufficiently well by the equation (6). When the pulse width is smaller than the channel width, the position of the leading edge t_{ol} of the pulse is first obtained from the data derived when the width was widened and it is added to a half of the pulse width to make an accurate assessment of t_o.

ii) Assessment of L

As to the effects of the steady neutron source, there is no problem if L (assuming S does not change) remains unchanged because the counting was made with the pulser turned off. Assuming that only ΔL changed, it would be the error of N_d. The trouble is that it is impossible directly to see whether the L observed is the same as that in the measurement of decay curve.

Here, an indirect method is used to study this problem.

The count of S + L measured, if the higher-order components is ignored, is equivalent to a multiplication of the source term $s + \ell$ which is independent of reactivity.

$$S + L = \frac{s+\ell}{1-Keff} \quad \cdots\cdots\cdots\cdots\cdots\cdots(7)$$

If this is rewritten by using the reactivity ρ_p obtained by the pulse method.

$$s + \ell = (S+L) \cdot \frac{\rho p \cdot \beta}{1+\rho p \beta} \quad \cdots\cdots\cdots\cdots\cdots\cdots(8)$$

Now, assuming that L decreased to become L' at the time of compensating experiment, Nd will accordingly increase to Nd' and ρ_p decreases to ρ_p'. Therefore, corresponding $s + \ell'$ in equation (8) becomes smaller than $s + \ell$ when L remained unchanged.

It is presumed that a knowledge of the variations of L will be obtained by comparing $s + \ell$ for several different degrees of reactivity. The results of calculations are shown in Table 5. From this, it is seen that the value of $s + \ell$ is very stable for Det. 3. Since ρ_p itself contains an error of 2 to 3% (excluding the variation in L), it is not easy to discuss quantitatively but

it would be allowable to presume that the variation in L, if any, would be only so much at most.

As to Det. 1, the value of $s + \not{\alpha}$ was not steady and increased toward the subcritical. This is presumably because Det. 1 was so close to the target that there were some direct counts without being multiplied.

iii) Assessment of F

In the present experiments, the pulser of the accelerator did not work very well and when the frequency changing switch was turned once, the frequency was deviated about 10% in the maximum. However, once it was set to a certain frequency, its deviation was 1% at most, and much better if an average in relation to time is taken.

V. Conclusion

We performed pulsed neutron experiments on a two-region system of a fast reactor core which contained a considerable quantity of plutonium and surrounded by natural uranium blankets by changing the reactivity from delayed critical to -6$. The results thus obtained were as follows.

(1) The effects of the spontaneous fission of plutonium as much as in the present experiments cause no trouble in carrying out experiments.

(2) The decay constant α_c at delayed critical is $0.341 \pm 0.013 \times 10^4$ sec^{-1}

The ratio of the calculated value to the experimental value is as follows, showing a similar tendency as in the case of uranium system.

$$\frac{\alpha_c\ (cal)}{\alpha_c\ (exp)} = 1.13 \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{J - F SNKPARAM}$$

(3) The decay constant, α showed a good agreement within the measured reactivity range regardless of detector positions and energy responses.

(4) The reactivity ρ_p which was obtained by the method of GOZANI based on a single exponential model also showed a good agreement.

(5) α and ρ_p held good linear relation from delayed critical down to -2$. Although the number of measurement points was small the obtained values were almost on a straight line down to -6$.

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Table 1. Atomic Concentrations for Assembly V－1.

Nuclide	Atom Densities. $\times 10^{24}$ Atoms/cm^3	
	Core	Blanket
Pu － 239	1.0446×10^{-3}	
Pu － 240	9.427×10^{-5}	
Pu － 241	1.124×10^{-5}	
U － 235	1.960×10^{-3}	2.891×10^{-4}
U － 238	7.781×10^{-3}	3.989×10^{-2}
O	1.6476×10^{-2}	
Na	6.0431×10^{-3}	
Aℓ	1.1065×10^{-2}	
Cr	3.0535×10^{-3}	1.827×10^{-3}
Fe	1.09705×10^{-2}	6.652×10^{-3}
Ni	1.4275×10^{-3}	7.964×10^{-4}

Critical Mass for V－1－D

Pu fiss. 64.907 Kg

U － 235 129.307 Kg

Table 2

Experimental Results of Pulse Method on FCA Assembly V－1							
Run No.	Core Pattern	ρ % $\Delta k/k$ source multiplication	Pulse Condition		* Detector	Decay Constant $\times 10^5$ sec^{-1}	Reactivity $-\rho$ ($)
			Width μs	Freq KHZ			
5/14 #6~10	Delayed critical	——	0.5	2	1	0.335 ± 0.013	——
5/14 #13~15	〃	——	2	2	2	0.344 ± 0.012	——
5/15 # 3	C/R # 2 Full out	0.125	0.1	2	3	0.415 ± 0.008	0.218 ± 0.005
5/15 # 1	〃	〃	2	2	1	0.412 ± 0.008	0.222 ± 0.006
5/15 # 5	〃	〃	2	2	2	0.411 ± 0.009	——
5/15 # 8	C/R #1, 2 Full out	0.516	0.1	2	3	0.637 ± 0.008	0.889 ± 0.016
5/15 # 6	〃	〃	2	2	1	0.652 ± 0.006	0.918 ± 0.012
5/15 #10	〃	〃	2	2	2	0.650 ± 0.018	——
5/18 # 1	C/R #1, 2 S/R #8, 9 Full out	1.20	0.2	5	3	1.054 ± 0.015	2.17 ± 0.05
5/18 # 2	〃	〃	〃	〃	3	1.051 ± 0.016	2.14 ± 0.06
5/18 #4A	〃	〃	2	5	1	1.060 ± 0.014	2.25 ± 0.05
5/18 #4B	〃	〃	〃	〃	1	1.071 ± 0.015	2.20 ± 0.06
5/18 # 6	All C/R, S/R Full out	2.42	0.2	5	3	1.827 ± 0.010	4.36 ± 0.05
5/19 # 1	C/R #1, 2 Full out Gap 20mm	2.53	0.2	5	3	1.945 ± 0.014	4.54 ± 0.09
5/18 # 8	All C/R, S/R Full out Gap 10mm	3.57	0.2	5	3	2.395 ± 0.012	6.24 ± 0.09

* Detectors : 1 ^{235}U micro fission chamber
2 ^{237}NP micro fission chamber
3 ^{235}U high sensitive fission chamber

Table 3、 β_i Values in FCA V－1

$\beta_i \times 10^5$

i	^{239}Pu	^{240}Pu	^{241}Pu	^{235}U	^{238}U
1	2.42	0.068	0.025	11.91	2.32
2	17.85	0.664	0.587	66.74	24.45
3	13.77	0.469	0.443	58.91	28.91
4	20.91	0.854	0.998	127.52	69.25
5	6.57	0.312	0.467	40.10	40.16
6	2.23	0.071	0	8.15	13.39
Total	63.75	2.44	2.52	303.56	178.47

Table 4 Comparison between Experimental and Calculated Values of α_c

Core No.	xss and code	Calculational Values			α_c(Exp)	$\frac{\alpha_c(Ca\ell)}{\alpha_c(Exp)}$
		ℓ($\times10^{-7}$ sec)	β($\times10^{-3}$)	α_c($\times10^{3}$ sec^{-1})		
Ⅱ－1	ABBN KPARAM	1.08	7.22	0.667	0.54 ±0.01	1.24
	JAERI－FAST SNKPARAM	1.20	7.11	0.594		1.10
Ⅱ－2	ABBN KPARAM	1.93	7.36	0.374	0.273 ±0.008	1.37
	JAERI－FAST SNKPARAM	2.50	7.04	0.281		1.03
V－1	ABBN KPARAM	1.30	5.63	0.433	0.341 ±0.013	1.27
	JAERI－FAST SNKPARAM	1.42	5.51	0.387		1.13
JOYO	ABBN KPARAM	1.91	5.23	0.273	——	——

Table 5. Comparison of Constant Source Component,

Run No.	Core Pattern	Detector No.	number of trigger	channel width	B/ch.	L+S/ch.	Nd/ch.	$X=\frac{L+S}{Nd}$	ρ_p	$s+\ell$
			$\times 10^6$	μs				%		sec^{-1}
5/15 # 3	C/R #2 Full out	3	4	1	2.844×10^{4}	1.392×10^{4}	1.452×10^{4}	95.9	0.218	4.17
5/15 # 8	C/R #1. 2 Full out	〃	4	1	2.85×10^{3}	1.68×10^{3}	1.17×10^{3}	144	0.889	4.09
5/18 # 1	C/R #1. 2 S/R #8. 9 Full out	〃	2	0.25	4.84×10^{2}	1.79×10^{2}	3.05×10^{2}	58.7	2.17	4.22
5/18 # 2	〃	〃	2	1	1.91×10^{3}	7.15×10^{2}	1.19×10^{3}	60.1	2.14	4.14
5/18 # 6	All C/R S/R Full out	〃	4	0.25	3.88×10^{2}	1.73×10^{2}	2.15×10^{2}	80.5	4.36	4.06
5/18 # 8	All C/R S/R Full out Gap 10mm	〃	4	0.25	2.32×10^{2}	1.25×10^{2}	1.07×10^{2}	117	6.24	4.15
5/15 # 1	C/R #2 Full out	1	4	1	7.95×10^{3}	3.07×10^{2}	7.64×10^{3}	4.01	0.22	0.094
5/15 # 6	C/R #1. 2	〃	4	1	9.83×10^{2}	8.32×10^{1}	9.00×10^{2}	9.24	0.918	0.105
5/18 #4B	C/R #1. 2 S/R #8. 9 Full out	〃	2	0.5	1.69×10^{2}	1.04×10^{1}	1.59×10^{2}	6.54	2.20	0.125

*

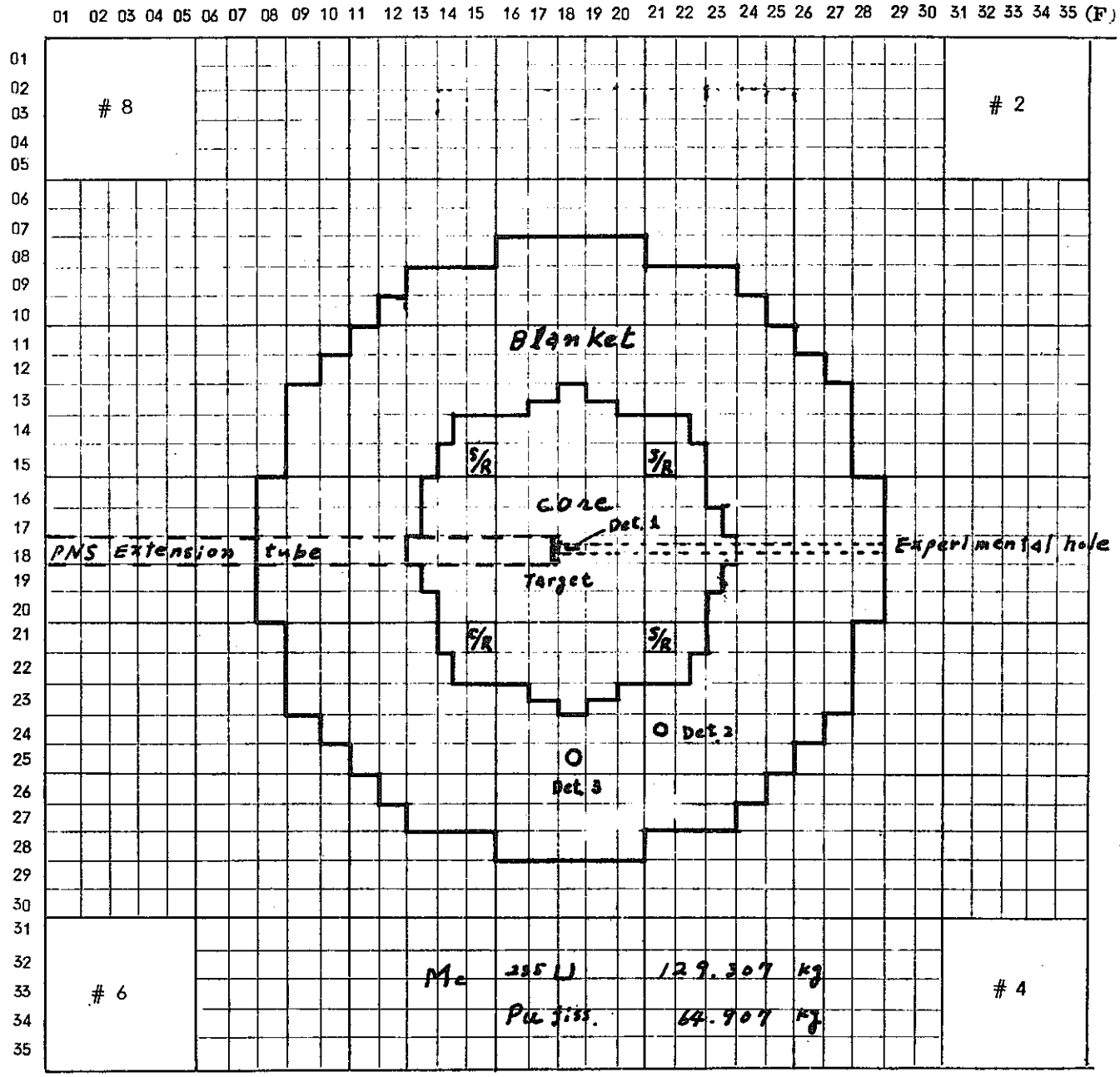

Fig. 1, V-1-D core pattern

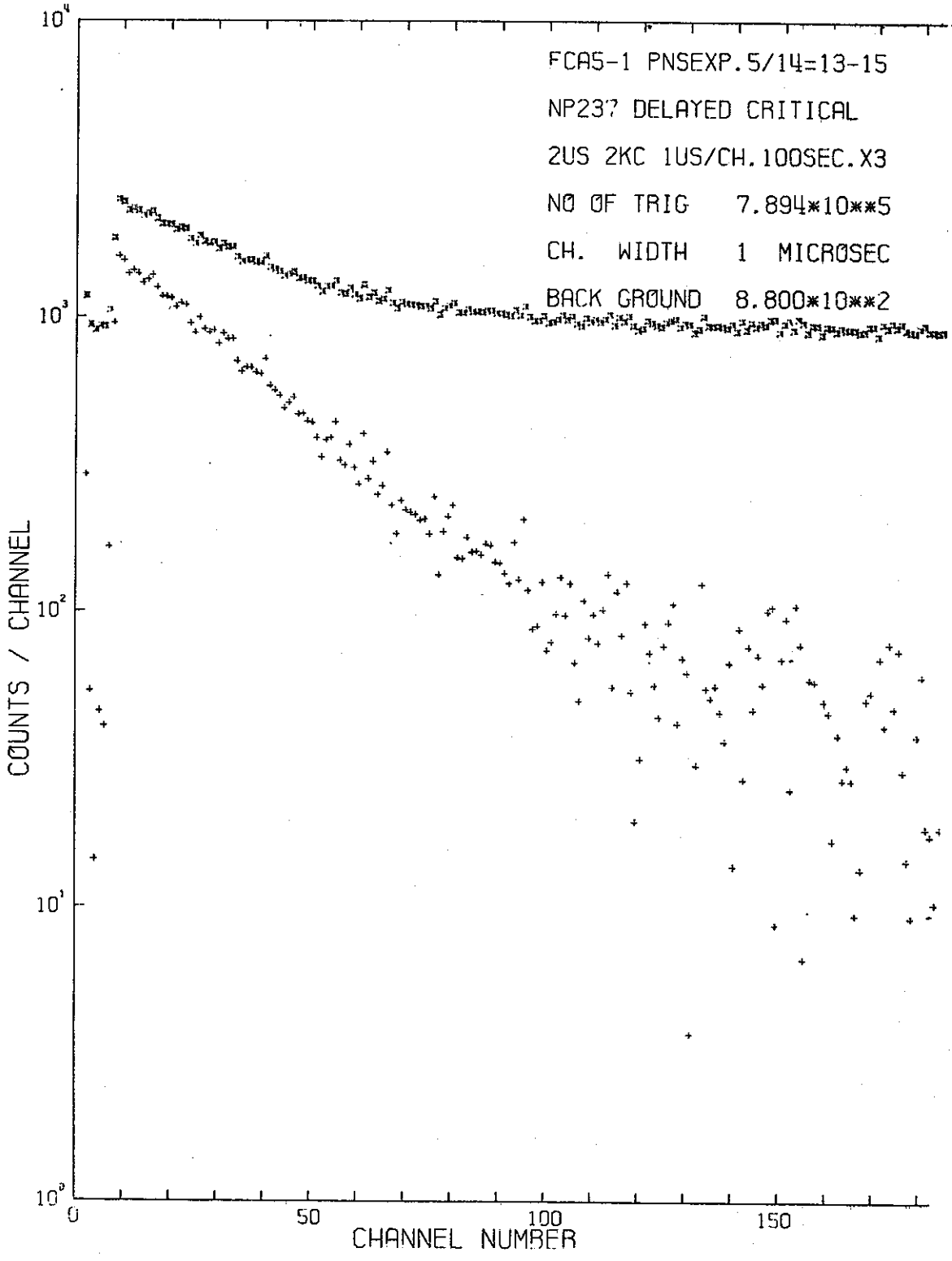

Fig. 2、 Decay curve (1)

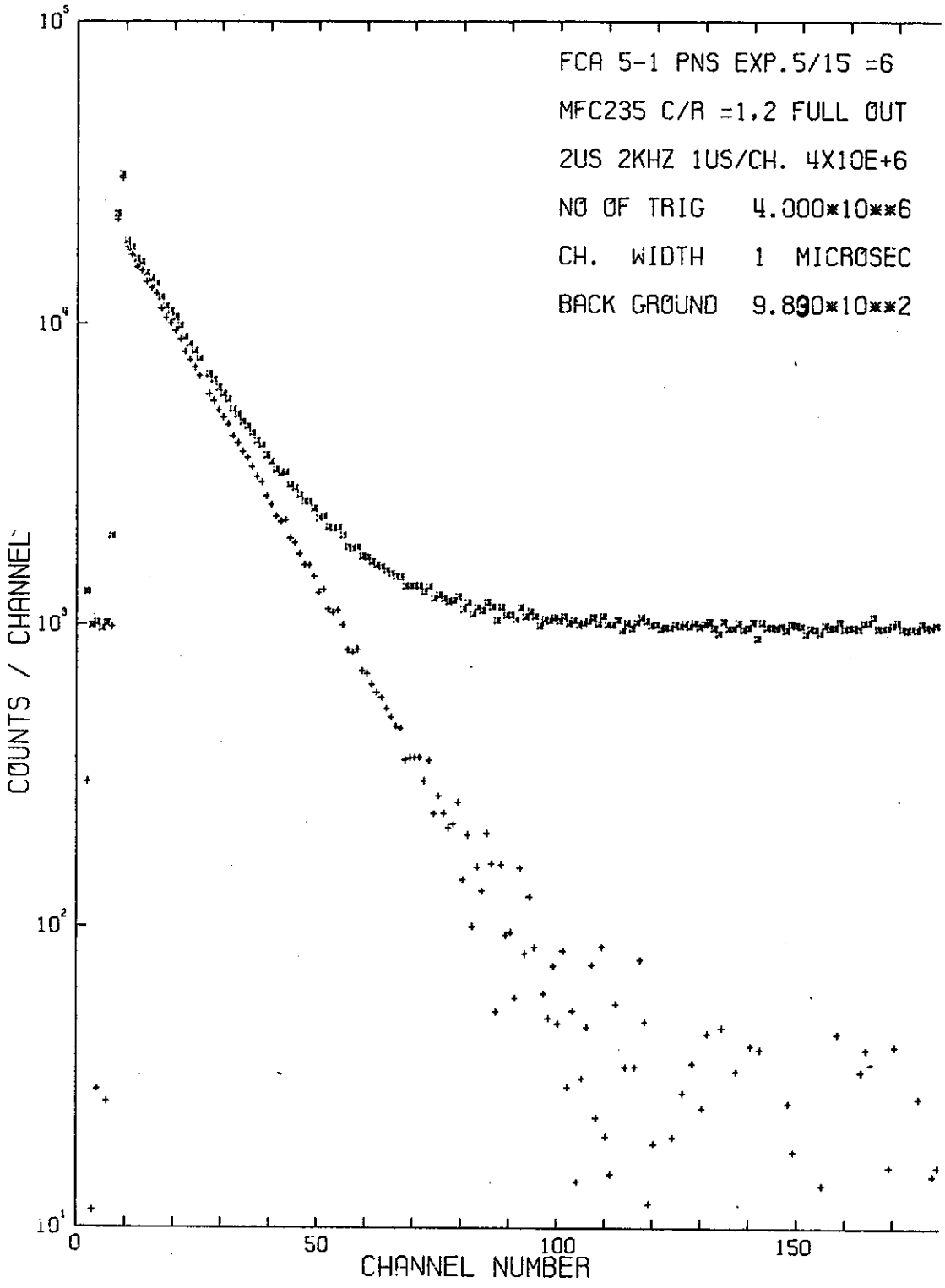

Fig. 3. Decay curve (2)

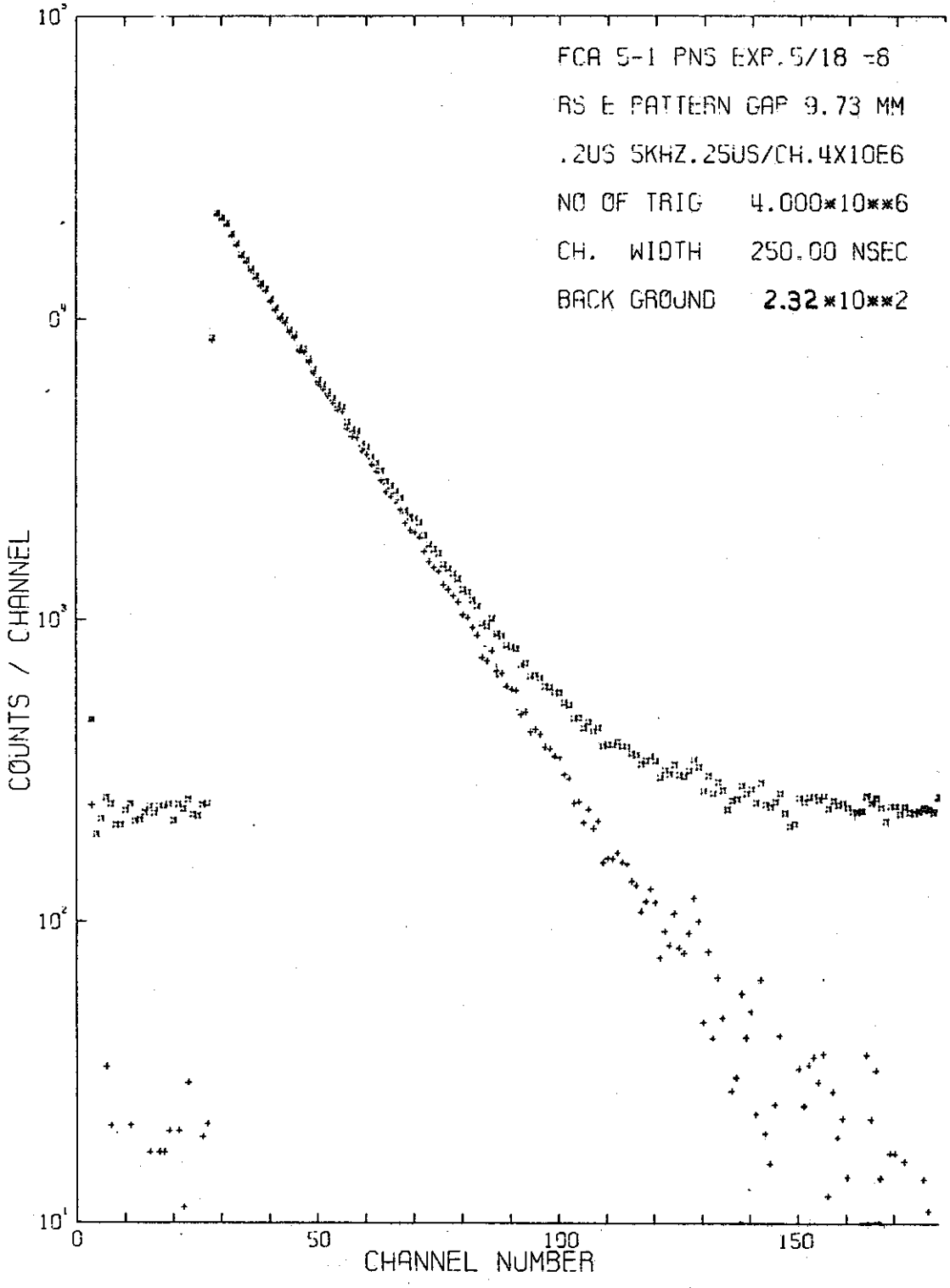

Fig. 4. Decay curve (3)

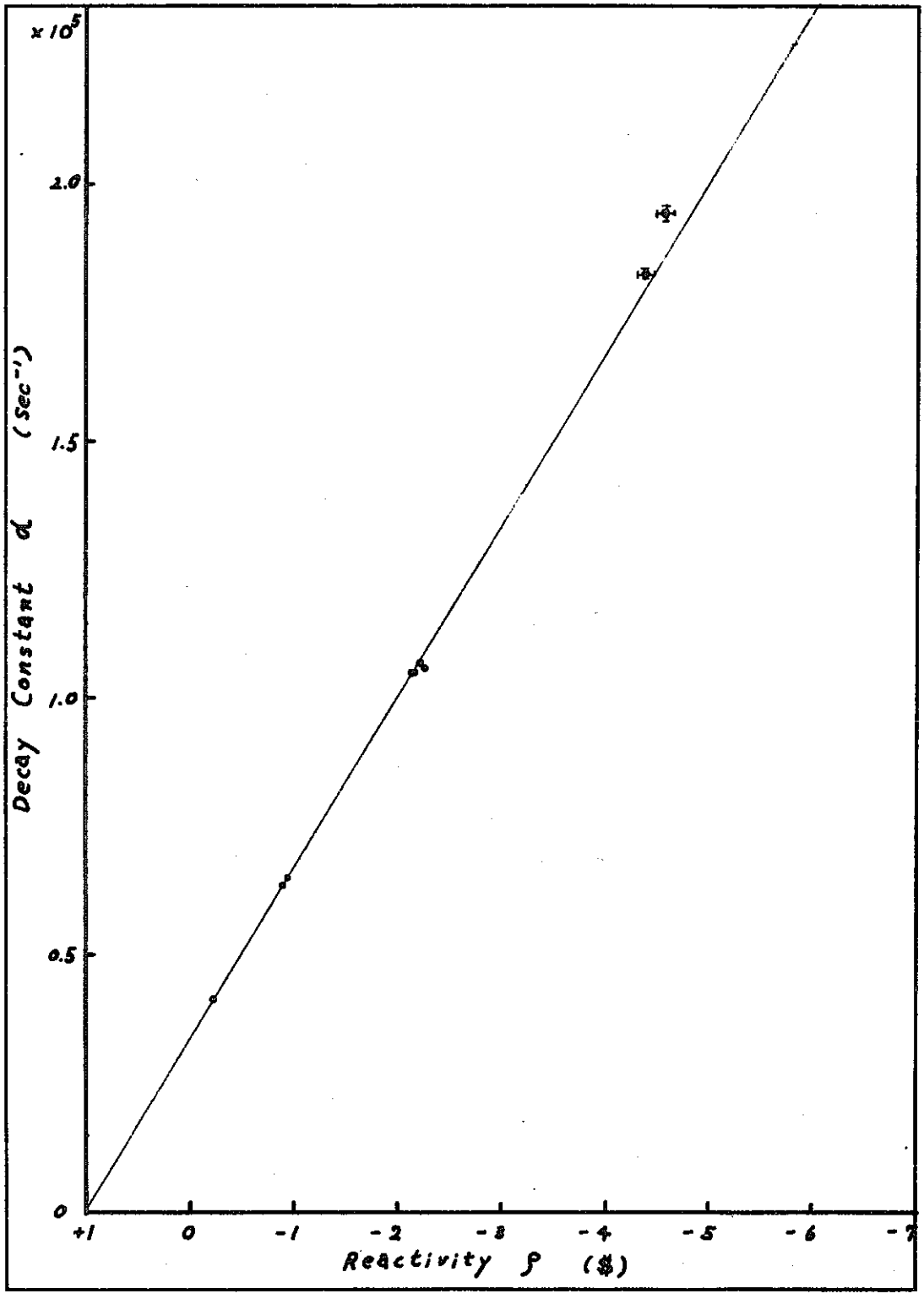

Fig. 5. Relation between decay constant α and reactivity ρ.

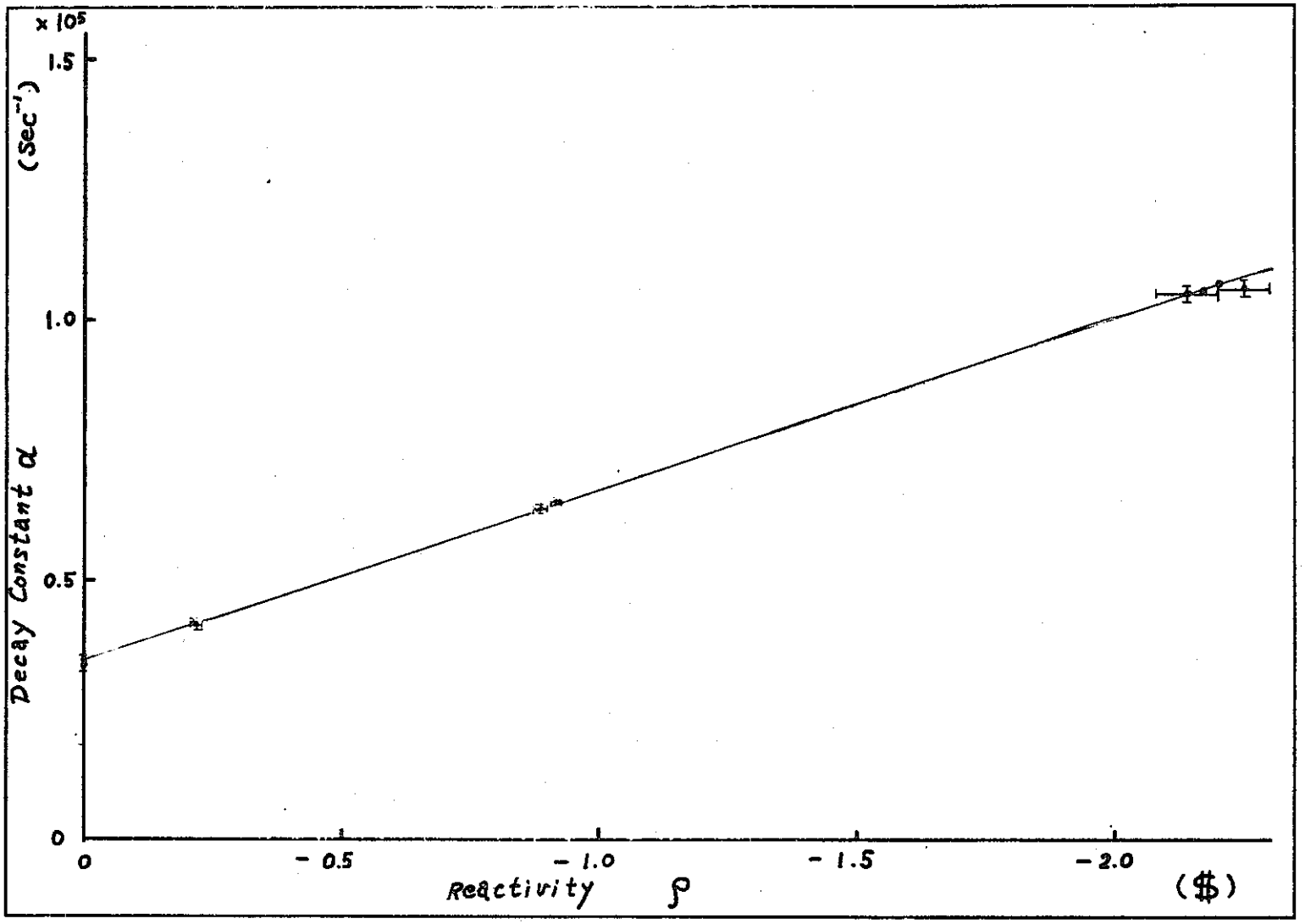

Fig. 6 Relation between decay constant α and reactivity ρ.