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PART I

COMMISSION OF THE EUROPEAN COMMUNITIES

COLLECTRONS, SELF-POWERED NEUTRON FLUX DETECTORS

Part I : Theoretical considerations

by

M. GRIN

1972

Joint Nuclear Research Centre
Ispra Establishment - Italy

Materials Division

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ABSTRACT

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KEYWORDS

NEUTRON DETECTION
NEUTRON FLUX
ELECTRIC CHARGES
EMISSION
BETA PARTICLES
SENSITIVITY
SELF-SHIELDING
RHODIUM
SILVER
VANADIUM

C O N T E N T S

1. INTRODUCTION *)

Neutron flux measurements during irradiation tests are normally performed by activation methods using wires or foils of suitable materials like Co, Ag, Ni, Au, In, Cu ... The amount of radioactivity induced during a controlled exposure is a measure of the neutron flux intensity : after exposure the activities measured are those of the emitted β or γ rays. The method is simple, rather accurate but gives only a mean value of the neutron flux during the whole exposure.

A direct measurement of the neutron flux is possible with fission chambers but they require a complex electronic associated equipment and are generally of notable dimensions : however a dealer proposes a sub-miniature fission chamber of 1 mm O.d. and 10 mm long [1].

After the theoretical and experimental works of MITELHAN [2], CESARELLI [3] and HILBORN [4], a new type of instantaneous flux detector was developped, the "collectron" or continuous neutron flux detector which is self powered, gives a signal directly proportional to the neutron flux and can be easily miniaturized.

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*) Manuscript received on January 5, 1972

2. DESCRIPTION AND WORKING PRINCIPLE OF THE COLLECTRON

2.1. Principle [2, 3, 4, 5, 6]

The detector consists of two coaxial electrodes : the inner electrode which is a β emitter is isolated from the outer electrode or collector (Fig.1). When a neutron flux impinges on the device, the inner electrode is activated and the emitted β particles are collected by the outer electrode : it is sufficient to close the circuit on a suitable measuring device to measure an electric current which, at saturation, is directly proportional to the neutron flux.

2.2. Realization and component materials

Geometrically, the detector is composed of a β emitter wire, a solid dielectric material (usually high purity Al_2O_3) and a sheath. The detector is then joined to a coaxial connecting cable (Fig. 1 and 2). The measured current is the resultant of β emission from the emitter and from some impurities always present in the sheath and in the connecting wires.

2.2.1. The emitter

The emitter must present a high cross-section to give a good sensitivity but not too much in order to limit the loss of sensitivity due to burn out. The radioactive half life for decay in the material should be of the order of 4 to 5 minutes for normal in-reactor applications. If other neutron absorbing isotopes are present in addition to the principal β emitter they must not produce long-lived β emitter that could cause slow variation of the measured current.

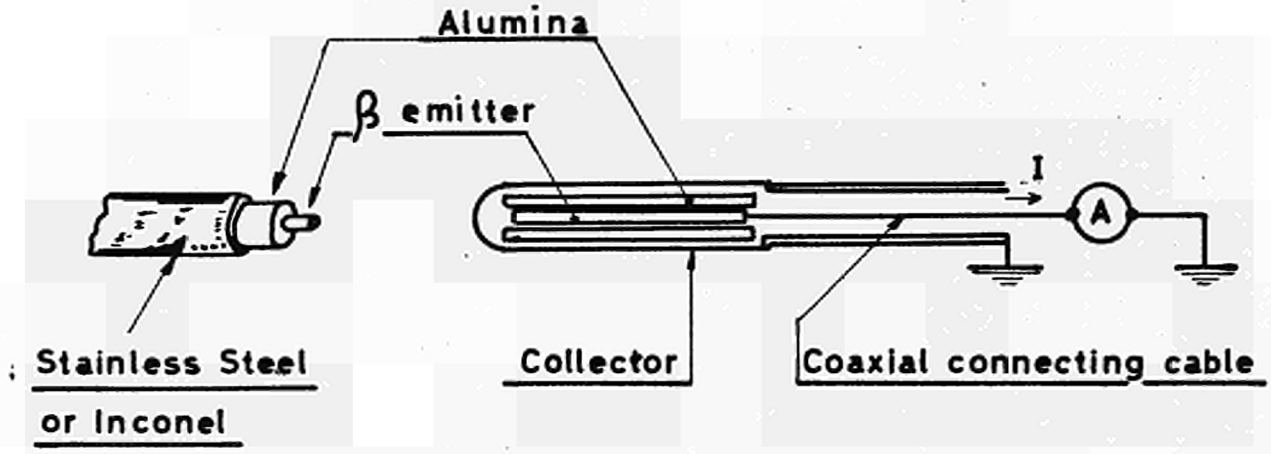


Fig. 1 . PRINCIPLE OF A COLLECTRON

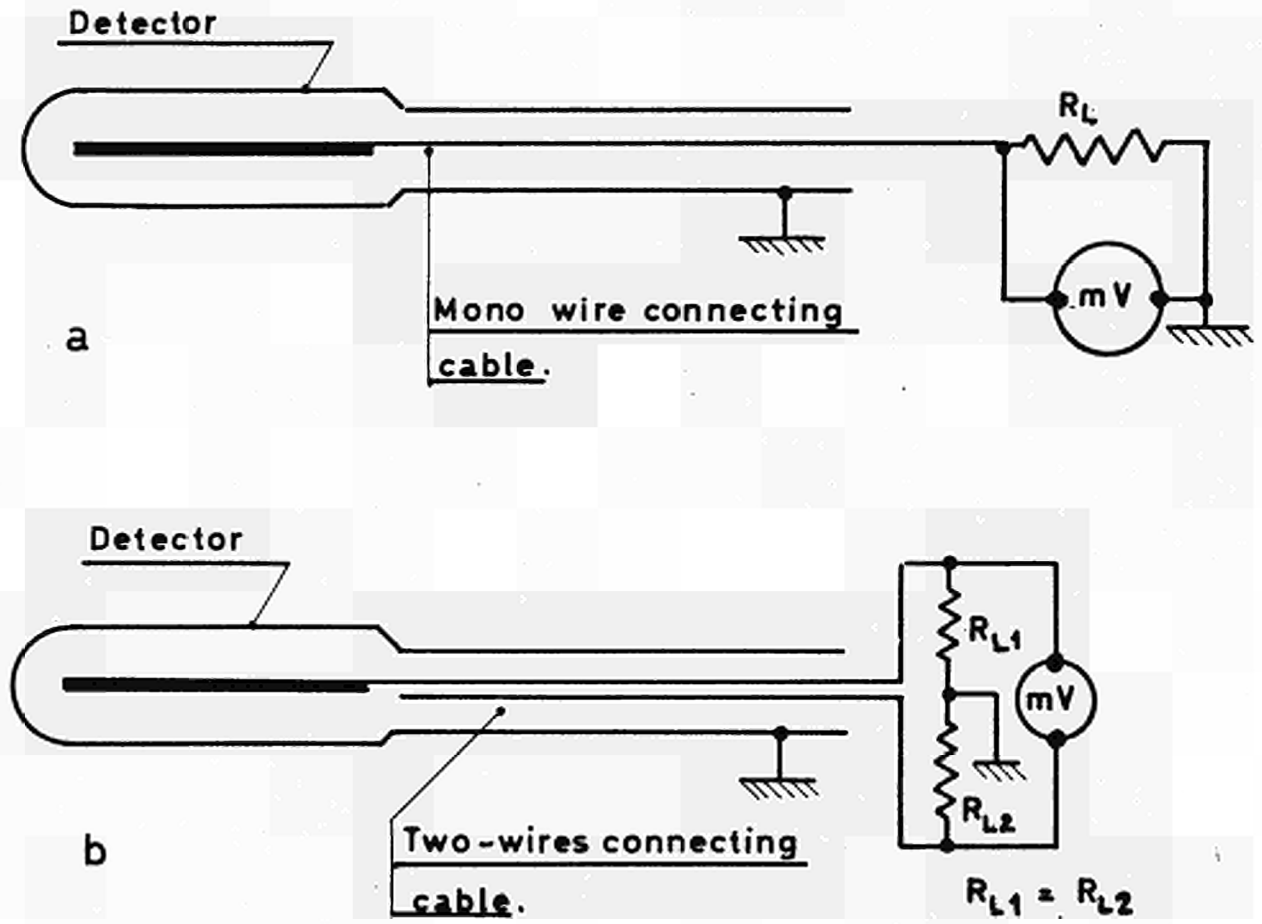


Fig.2 MEASURING CIRCUITS

a - normal wiring

b - background compensation circuit

Emitter	Abundance %	Cross sections at 2,200 m/s (barns) [7]		Westcott factors at 20°C [8]		Capture-product half life	Spectrum max.energy (Mev)	1st resonance peak (ev)
		abs	act	g	s			
V^{51}	99.76		4,5±0,9	1.00	0.0	3.76 m	2.6	185
Rh^{103}	100	156±7*	12 ± 2	1.023	7.255***	4.4 m		
			140 ± 30			42 sec	2.44	1.26
						99.9% of 4.4 m → 42 sec		
Ag^{107}	51.35	31±2	45 ± 4			2.3 m	1.56	16.5
				1.0044	14.12			
Ag^{109}	48.65	87±7	3.2±0.4			270 j**	2.87	5.2
			113 ± 13			24.2 s		
						5% of 270 j → 24.2 sec		

* Westcott (AECL) counsels the normalized value of 150.19

** negligible, 1 % of signal after 1 year in a flux of 10^{13} n.cm^{-2} s^{-1}

*** S 4

TABLE I - Neutronic characteristics of β emitters employed for the realization of collectrons

The maximum energy of β spectrum must be high to allow the β to escape from the insulant and from the emitter wire itself.
All these conditions limit normally the choice of emitter to Rhodium, Vanadium or Silver whose main characteristics are summarized in Table 1.

2.2.2. The sheath or collector

Normally choosen with regard to applicability (weldability, compatibility in normal working conditions) the collector is usually (as the sheath of the connecting cable) a tube of stainless steel or inconel with a thickness sufficient to stop β particles emitted from the central wire.

2.2.3. Connecting cable

It is a miniature sheathed cable of the type normally employed for temperature measurements : the sheath is in stainless steel or inconel, the wires (or the wire) are in Ni, the insulant is usually MgO.
This connecting cable can be the origin of spurious currents and (or) electric leakage. Theoretically a compensating wiring (see § 2.3.) can eliminate spurious currents from the coonecting cable.

2.3. Measuring circuit

It is possible to measure either directly the current, or, more simply, the tension at the terminals of a load resistance according to Fig. 2 a. It is obvious that the cable leakage resistance R_I must be large compared to the load resistance R_L.

Or, if R_1 is very high under the laboratory conditions at the moment of the fabrication of the detector ($R_1 \geqslant 10^4$ MΩ) it falls drastically in normal working conditions (influence of temperature and irradiation on the insulant, see § 3.6). The connecting cable, which is always partially submitted to neutron flux can be the origin of spurious currents : in fact either the sheath or the connecting wires contain traces of β emitters and it is possible to obtain a secondary current coming from the connecting cable in addition to the main signal of the detector. Theoretically, a compensating wiring, as indicated in Fig. 2 b allows to eliminate this parasitic effect.

3. THEORETICAL SENSITIVITY OF THE COLLECTRONS

In the simplest case, when activation is due to a single emitter nuclide, the output current, as a function of time after exposure to the neutron flux, is given by :

$$I_T = K.N.\ \phi.\ e.\ \hat{\sigma}\ [1 - \exp(0{,}693\ t/T_{1/2})] \quad (1)$$

N = number of atoms with $T_{1/2}$

ϕ = Westcott flux $\quad \phi = nv_o$

$\hat{\sigma}$ = Westcott activation cross-section

$\hat{\sigma} = \sigma_o\ (g + rs)$

e = electronic charge $\quad 1.602\ \ 10^{-19}$ coulomb

$T_{1/2}$ = half-life of the emitter

K = constant depending on geometry, beta self-absorption and neutron flux depression in the detector.

The response time T_R , which is the time requested to obtain 63 % of the saturation signal corresponding to an instantaneous neutron flux variation, is defined as :

$$T_R = 1.44 \; T_{1/2}$$

The equilibrium output, or saturation signal, reached after some $T_{1/2}$ is thus :

$$I_s = K.N.\phi.e.\hat{\sigma} \qquad (2)$$

All neutron detectors gradually lose sensitivity, due to burn out of the neutron sensing β emitter.
If N is the number of stable isotopes at instant 0 (beginning of irradiation), after the time t, it remains :

$$N = N_o \; \exp (- \hat{\sigma} . \phi . t)$$

and the equilibrium output becomes :

$$I_s = K_i . N_o . \phi . e . \hat{\sigma} . \exp (- \hat{\sigma} . \phi . t)$$

3.1. Evaluation of the correcting factor K

In first approximation K may be considered as the product of two factors :

$$K = K_1 . K_2$$

where :

K_1 = neutron self-shielding and flux depression factor

K_2 = self-absorption factor of β particles in the emitter (and in the insulant)

K_1 and K_2 must evidently take into account the geometrical configuration of the device.

3.1.1. Self-shielding and flux depression factor K_1

Generally speaking, the presence of an absorber of macroscopic size in a neutron flux modifies the flux : it cannot be assumed that the flux in the absorber position is the same as that which would exist in that position if the absorber were absent. In general, the absorber will depress the flux in its vicinity.

KUSHNERIUK [9] has shown that the ratio of mean flux to surface flux in an infinite long cylindrical absorber surrounded by an infinite predominantly scattering medium sustaining a thermal neutron flux, is adequately represented by the following formula :

$$\frac{\bar{\phi}}{\phi_o} = \frac{1}{a.\Sigma a} \cdot \frac{\beta}{2-\beta}$$

where

a = radius of the cylinder

Σ_a = macroscopic absorption cross section

β = Probability that a neutron falling in the surface of the rod will be absorbed within it.

If Σ_s is the macroscopic scattering cross-section and Σ_t the macroscopic total cross-section, β can be represented by the following expression valid for a $\Sigma_t < 2.5$

$$\beta = \frac{a.\Sigma_a.P_1\ (a.\Sigma_a + a.\Sigma_s)}{a.\Sigma_a + a.\Sigma_s.P_{ES}(a\Sigma_a + a\Sigma_s)}$$

where

$P_1 (a\Sigma_t)$ = probability that a neutron, thrown into the absorber from a constant and isotropic source density in an infinite medium surrounding the absorber, undergoes collision within the cylindrical absorber.

$P_{ES} (a\Sigma_t)$ = collision escape probability for an isotropic source distribution within the cylindrical absorber.

In these conditions :

$$K_1 = \frac{\bar{\phi}}{\phi_o} = \frac{P_1 (a.\Sigma_t)}{a\Sigma_a . [2 - P_1(a\Sigma_t)] + 2a.\Sigma_s . P_{ES}(a\Sigma_t)} \quad (3)$$

$$a.\Sigma_t = a.\Sigma_a + a.\Sigma_s$$

P_1 and P_{ES} are given for varying $(a\Sigma_t)$ in Fig. 3.

Moreover Mc GILL and al. [10] have made experimental measurements whose results are in good agreement with the KUSHNERIUK's computation.

For values of $a\Sigma_a$ up to ~ 0.8 they propose the empirical correlation :

$$K_1 = \frac{2}{K.a} \cdot \frac{I_1(Ka)}{I_o(Ka)} \quad (4)$$

with $K = C \left(\frac{\Sigma_a}{a}\right)^{1/2}$

$C = 0.183 \pm 0.13$

I_o and I_1 are Bessel's functions.

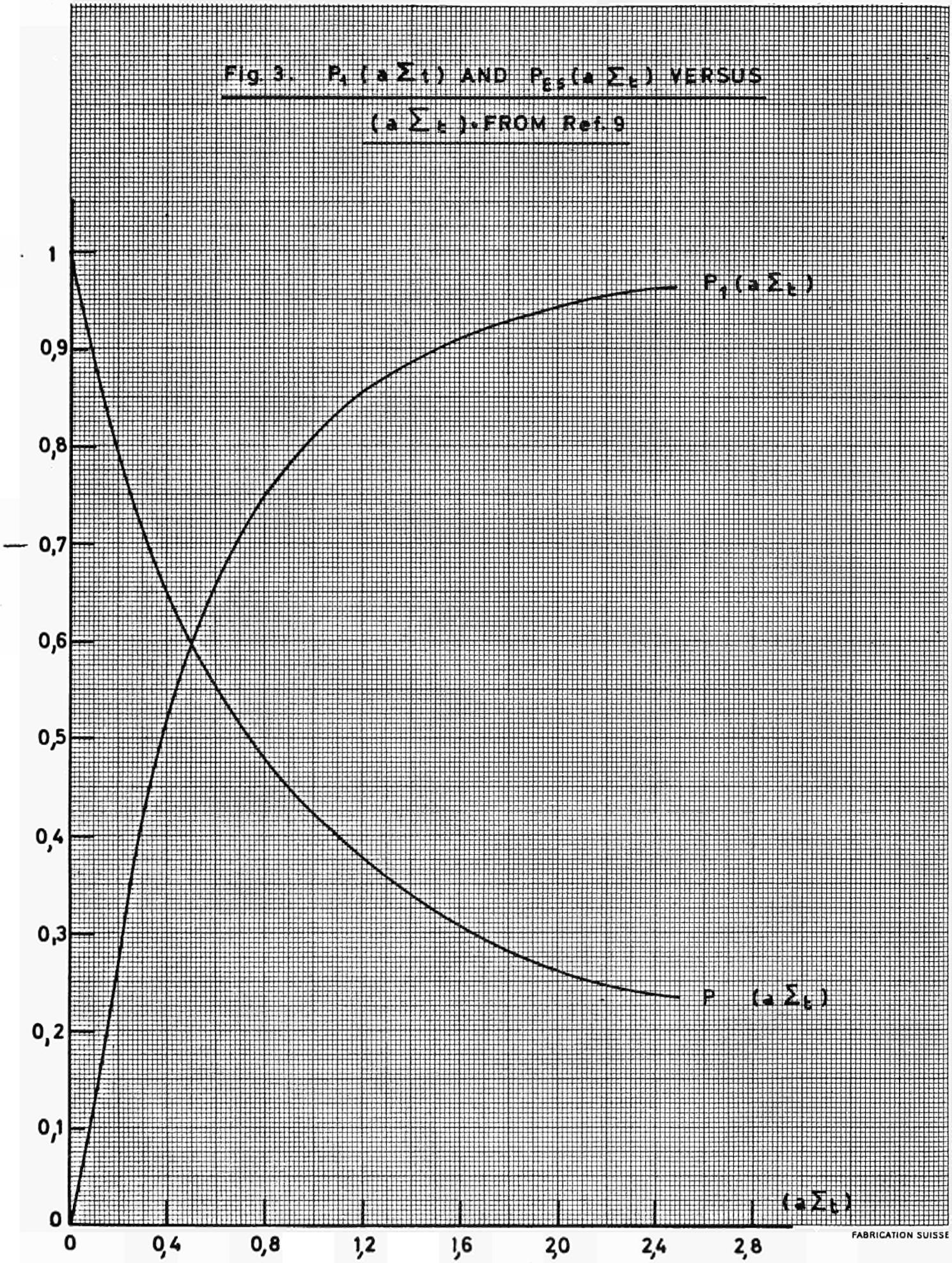


Fig. 3. $P_1(a\Sigma_t)$ AND $P_{ES}(a\Sigma_t)$ VERSUS $(a\Sigma_t)$. FROM Ref. 9

The experimental and calculated values are in good agreement with the computation made according to the Kushneriuk's formula. The % error between the two methods (5 to 10 %) is of the same order of magnitude as the experimental measurements.

Values of K_1 obtained by the two methods are compiled in Table 2.

Emitter	a(cm)	macroscopic cross section * (cm^{-1})			$a \cdot \Sigma_a$	K_1	
		a	s	t		Formula 3	Formula 4
Vanadium	0.05	0.352	0.352	0.704	0.0176	**	0.99
	0.025				0.0088	**	0.99
Rhodium	0.05	10.9	0.366	11.3	0.545	0.83	0.82
	0.025				0.272	0.91	0.90
Silver	0.05	3.69	0.352	4.04	0.184	0.88	0.93
	0.025				0.092	0.92	0.96

TABLE 2 : Flux depression factor K_1

* from ANL 2nd edition

** non calculated because of the magnitude of errors due to P_1 and P_{ES} for values of $a\Sigma_a$ close to zero.

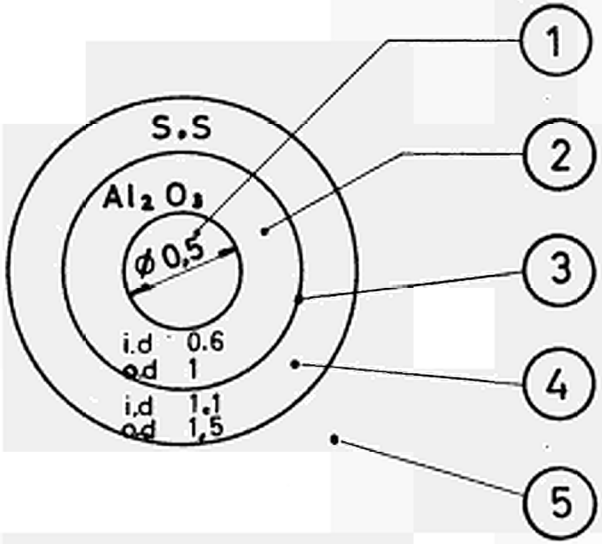
Values of K_1 have been calculated for neutrons at 2,200 m/s; they must be corrected for the Westcott flux and the neutron temperature.

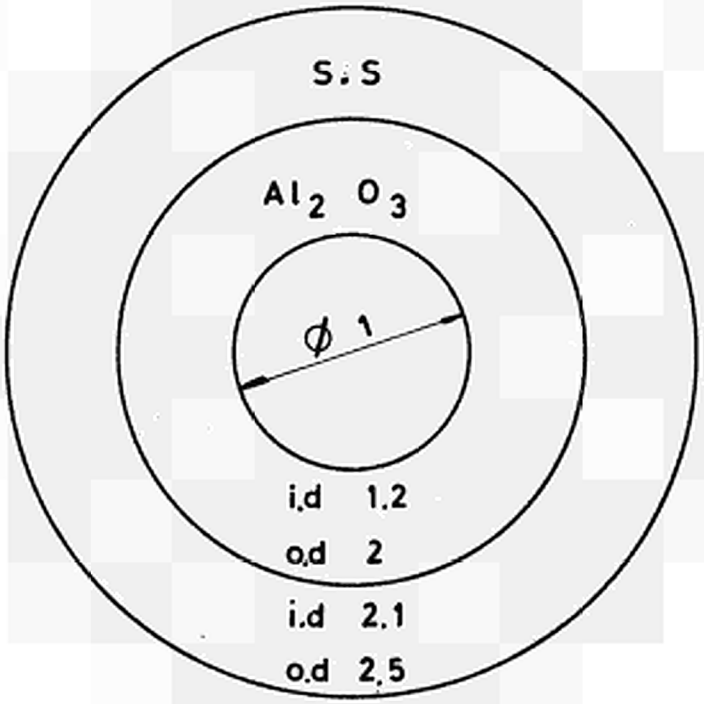
Preceding methods do not allow to take into account the effects due to sheath and insulant. In fact some elaborated nuclear codes exist which are able to take into account all the constitutive elements of a collectron.
The use of a WDSN code [11] leads to the results of Table 3. The computation was made, considering on one hand, the shielding effect due to the single emitter and, on the other hand, the global effect due to the whole detector according to the geometrical conditions of Fig.4, in which are also indicated the nuclear data adopted.

Emitter		K_1	
Material	Radius cm	due to the single emitter	due to the whole detector
V	0.05	0.99	0.99
	0.025	0.99	0.99
Rh	0.05	0.71	0.56
	0.025	0.86	0.75
Ag	0.05	0.90	0.83
	0.025	0.95	0.90

TABLE 3 - Computation of K_1 according to a nuclear code.

With respect to the preceding results the only sensible difference regards the rhodium, The additional effect of sheath and insulant is in the range of 10 %.





CONSIDERED GEOMETRIES
ALL DIMENSIONS IN m m .

		Σ_a	Σ_s
1	Rh	9,657	0,366
	Ag	3.269	0,352
	V	0,288	0,325
2	Al_2O_3	0.00883	0,318
3	Void	0	0
4	Stainless Steel	0,218	0.869
5	D_2O	$3.3\ 10^{-5}$	0,449

NUCLEAR DATA ADOPTED

Fig. 4 - COMPUTATION OF K 1 FROM A NUCLEAR CODE

3.1.2. Self-absorption factor K_2

To each monoenergetic β particle is associated a maximum range λ (which is normally expressed in the form of $\lambda \cdot \rho$ in mg/cm^2 of aluminium).
The probability for a β particle emitted from a point of a cyclindrical source of radius a to escape from the cylinder is a function of a and λ. For example, a β particle formed in the center of a rod, with a range less than the radius of the rod, would not escape.

The same β particle might escape if it were formed near the edge of the rod, depending on the direction of travel. If a sphere, with a radius equal to the range λ of the considered particle is placed with its center coincident with the origin of the β particle, the escape probability is the ratio of the area of the sphere that is outside of the rod divided by the total area of the sphere. It is possible to make a complete computation from this model [12], but it is easier to use the following formula, valid for a cylindrical emitter the diameter of which is low with respect to the length.

$$K_2 = \frac{\lambda}{a} \left[0.5 - F_2 \left(\frac{a}{\lambda}\right)\right] \qquad [13]$$

λ = range of the particle in cm.

a = radius of cylinder in cm.

$F_2 \left(\frac{a}{\lambda}\right)$ integral function defined by :

$$F_2(q) = q^2 E_3(q)$$

with $E_3(q) = \int_q^\infty \frac{e^{-p}}{p^3} \cdot dp$

Values of E_n (q) and F_2 (q) are tabulated in Annex I or in Ref. [14].

The range λ must be calculated from empirical formulas like :

$\lambda \cdot \rho = 0.543\ E - 0.16$ [13] valid for aluminium between 0.8 and 3 Mev but extrapolable to other materials,

$\lambda \cdot \rho = 0.142\ E^{1.265} - 0.0954 \log E$ [15]

valid for $0.01 < E < 2.5$ Mev

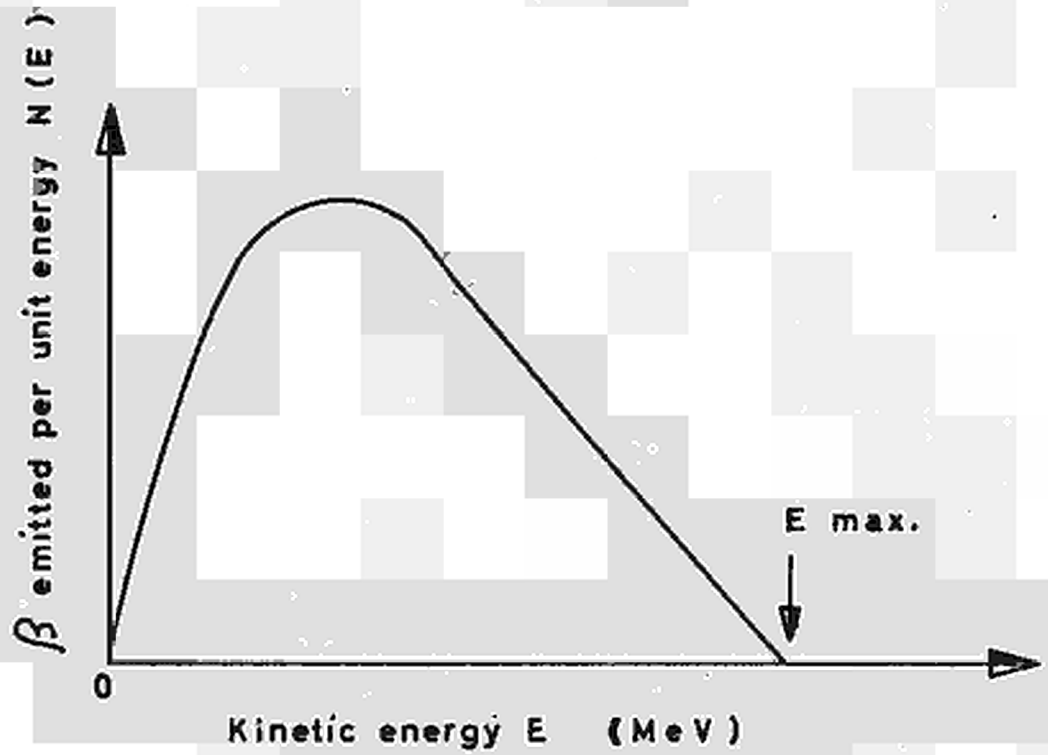
$\lambda \cdot \rho = 0.53\ E - 0.106$ [15]

valid for $E > 2.5$ Mev

where ρ is the density of the considered material.

The computation of K_2 is complicated by the fact that β particles are emitted with a continuous energy spectrum with energies varying from 0 to a maximum value which is considered as characteristic of the β emitter considered. A general shape of a β spectrum of energies is given by Fig. 5.

To each number N_i of β particles of a given energy must be associated a range λ_i which allows to calculate a corresponding value K_i of the self absorption factor. The value of K_2, for the considered reaction, is the integral of these elementary K_i values. An approximate value of the solution can be obtained in assimilating the β energy spectrum to a sum of rectangles to each of which is associated a mean number N_i and a mean energy E_i.



5 - β SPECTRUM

For each elementary rectangle it is possible to compute a mean absorption factor K_i ; approached value of K_2 is then given by the sum :

$$K_2 = \frac{\sum N_i \; K_i}{\sum N_i}$$

The only difficulty consists in determining the β energy spectrum of the considered reaction.

In the litterature it is possible to find values of maximum energy E max. which are normally used in radiation protection; the few experimental β spectra existing are related to elements with a rather long half-life which is evidently not the case of Rh, Ag, V. The only alternative consists in calculating, for each considered element, the theoretical corresponding β spectrum, or to use an empirical formula giving, for the whole spectrum, a mean energy value.

a) <u>determination of K_2 from a theoretical β energy spectrum.</u>
The computation, detailed in Annex 2, has been made in the case of Rh^{104}. The corresponding value of K_2 is 0.41.

b) <u>determination of K_2 from a mean energy value.</u>

A mean energy value (at $\pm$ 5%) of a β spectrum can be derived from the following formula :

$$\bar{E} = 0.33 \; E \left(1 - \frac{Z^{1/2}}{50}\right) \left(1 + \frac{E^{1/2}}{4}\right) \quad [15]$$

where : E = maximum energy in Mev

Z = atomic number of the stable isotope.

Always in the case of Rh^{104} where E max. = 2 and Z = 45 this formula gives $\bar{E} = 0.967$ which leads to a value of 0.43 for K_2.

This value is a justification of the validity of this determination and the results obtained, according to the application of this formula, are summarized in Table 4 for Rh, Ag and V in 0.5 mm diameter.

Emitter	Isotopic abundance %	Energy (Mev)		K_2
		E max.	$\bar{E}$	
Rh^{104}	100	2.44	0.97	0.43
Ag^{108}	51.35	1.56	0.59	0.29
Ag^{110}	48.65	2.87	1.16	0.54
V^{52}	100	2.60	1.08	0.62

TABLE 4 - Values of K_2 computed from mean energy values

3.2. Sensitivity of the collectrons

With the values of K_1 and K_2 it is now possible to calculate the theoretical sensitivity of the different β emitters according to formula (1). For thermal neutrons at 2,200 m/s and neglecting the possible effects of resonance phenomena in the epithermal region, the theoretical values of the saturation current are given in Table 5 for the different emitters considered.

Emitter	σ_{20} barn	$K = K_1 . K_2$	I_s corrected A per neutron
V^{52}	4.5	0.61	$0.066 . 10^{-21}$
Rh^{104}	150.19	0.39	$1.34 . 10^{-21}$
Ag^{108}	60	0.27	$0.416 . 10^{-21}$
Ag^{110}	60	0.50	

TABLE 5 - Theoretical values of the saturation current for various emitters of Ø 0.5 mm and 10 mm long.

As neither the silver nor the rodhium follow a $\frac{1}{v}$ law, it is necessary for these elements to correct the values obtained for the Westcott cross section which depends on the condition of irradiation. Moreover all values must be corrected for the neutron temperature.

4. LOSS OF SENSITIVITY OF THE VARIOUS β EMITTERS AS A FUNCTION OF NEUTRON DOSE

Due to irradiation the number of stable isotopes diminishes with increasing neutron exposure and consequently the sensitivity of the detector diminishes with neutron exposure. In Table 6 is indicated the loss of sensitivity (in % with respect to initial sensitivity) in function of the integrated flux for various emitters.

Emitter	Integrated flux (n. cm^{-2} . s^{-1})				
	10^{20}	5.10^{20}	10^{21}	5.10^{21}	10^{22}
V	0.045	0.22	0.45	2.25	4.5
Ag	0.44	2.2	4.4	22	44
Rh	1.5	7.5	15	75	

TABLE 6 - Loss of sensitivity versus integrated neutron flux.

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A N N E X 2

Numerical values of the functions :

$$E_3 \ (q) \equiv \int_q^{\infty} \frac{e^{-p}}{p^3} \cdot dp$$

$$F_2 \ (q) \equiv \quad q^2 \ ; \ E_3 \ (q)$$

Values of E_3 have been computed in CETIS (C.C.R.ISPRA) in assimilating the integral to a sum of trapezia : thus the tabulated values are slightly higher than the theoretical ones.

	q	$E_3(q)$	$F_2(q)$
1	10.00000E-03	4.9290E 03	4.9290E-01
2	1.07227E-02	4.2813E 03	4.9225E-01
3	1.14976E-02	3.7183E 03	4.9154E-01
4	1.23285E-02	3.2291E 03	4.9079E-01
5	1.32194E-02	2.8039E 03	4.8999E-01
6	1.41747E-02	2.4344E 03	4.8913E-01
7	1.51991E-02	2.1133E 03	4.8821E-01
8	1.62975E-02	1.8344E 03	4.8723E-01
9	1.74753E-02	1.5920E 03	4.8618E-01
10	1.87382E-02	1.3815E 03	4.8506E-01
11	2.00923E-02	1.1976E 03	4.8347E-01
12	2.15443E-02	1.0389E 03	4.8220E-01
13	2.31013E-02	9.0100E 02	4.8084E-01
14	2.47708E-02	7.8128E 02	4.7939E-01
15	2.65609E-02	6.7732E 02	4.7784E-01
16	2.84804E-02	5.8706E 02	4.7618E-01
17	3.05386E-02	5.0870E 02	4.7442E-01
18	3.27455E-02	4.4069E 02	4.7254E-01
19	3.51119E-02	3.8167E 02	4.7054E-01
20	3.76494E-02	3.3045E 02	4.6840E-01
21	4.03702E-02	2.8601E 02	4.6613E-01
22	4.32876E-02	2.4727E 02	4.6334E-01
23	4.64159E-02	2.1388E 02	4.6078E-01
24	4.97702E-02	1.8492E 02	4.5806E-01
25	5.33670E-02	1.5982E 02	4.5516E-01
26	5.72237E-02	1.3806E 02	4.5208E-01
27	6.13591E-02	1.1921E 02	4.4882E-01
28	6.57933E-02	1.0288E 02	4.4535E-01
29	7.05480E-02	8.8675E 01	4.4134E-01
30	7.56463E-02	7.6448E 01	4.3746E-01
31	8.11131E-02	6.5866E 01	4.3336E-01
32	8.69749E-02	5.6713E 01	4.2901E-01
33	9.32603E-02	4.8798E 01	4.2442E-01
34	10.00000E-02	4.1957E 01	4.1957E-01
35	1.07227E-01	3.6021E 01	4.1415E-01
36	1.14976E-01	3.0922E 01	4.0878E-01
37	1.23285E-01	2.6522E 01	4.0312E-01
38	1.32194E-01	2.2727E 01	3.9716E-01
39	1.41747E-01	1.9455E 01	3.9090E-01
40	1.51991E-01	1.6625E 01	3.8407E-01
41	1.62975E-01	1.4202E 01	3.7721E-01
42	1.74753E-01	1.2117E 01	3.7003E-01
43	1.87382E-01	1.0325E 01	3.6252E-01
44	2.00923E-01	8.7796E 00	3.5444E-01
45	2.15443E-01	7.4607E 00	3.4629E-01
46	2.31013E-01	6.3301E 00	3.3782E-01
47	2.47708E-01	5.3621E 00	3.2901E-01
48	2.65609E-01	4.5314E 00	3.1968E-01
49	2.84804E-01	3.8250E 00	3.1026E-01

EURATOM - C.C.R. ISPRA - CETIS

	q	$E_3(q)$	$F_2(q)$
50	3.05385E-01	3.2225E 00	3.0053E-01
51	3.27455E-01	2.7092E 00	2.9050E-01
52	3.51119E-01	2.2714E 00	2.8003E-01
53	3.76493E-01	1.9011E 00	2.6948E-01
54	4.03702E-01	1.5873E 00	2.5869E-01
55	4.32876E-01	1.3209E 00	2.4752E-01
56	4.64159E-01	1.0970E 00	2.3634E-01
57	4.97702E-01	9.0829E-01	2.2499E-01
58	5.33670E-01	7.4923E-01	2.1338E-01
59	5.72237E-01	6.1639E-01	2.0184E-01
60	6.13591E-01	5.0530E-01	1.9024E-01
61	6.57933E-01	4.1267E-01	1.7863E-01
62	7.05480E-01	3.3550E-01	1.6698E-01
63	7.56463E-01	2.7176E-01	1.5551E-01
64	8.11131E-01	2.1914E-01	1.4418E-01
65	8.69749E-01	1.7577E-01	1.3296E-01
66	9.32603E-01	1.4035E-01	1.2207E-01
67	10.00000E-01	1.1146E-01	1.1146E-01
68	1.07227E 00	8.7967E-02	1.0114E-01
69	1.14976E 00	6.9040E-02	9.1267E-02
70	1.23285E 00	5.3833E-02	8.1822E-02
71	1.32194E 00	4.1667E-02	7.2814E-02
72	1.41747E 00	3.2032E-02	6.4359E-02
73	1.51991E 00	2.4432E-02	5.6440E-02
74	1.62975E 00	1.8472E-02	4.9063E-02
75	1.74753E 00	1.3850E-02	4.2297E-02
76	1.87382E 00	1.0287E-02	3.6120E-02
77	2.00923E 00	7.5609E-03	3.0524E-02
78	2.15443E 00	5.5010E-03	2.5533E-02
79	2.31013E 00	3.9568E-03	2.1116E-02
80	2.47708E 00	2.8105E-03	1.7245E-02
81	2.65609E 00	1.9717E-03	1.3910E-02
82	2.84803E 00	1.3642E-03	1.1066E-02
83	3.05385E 00	9.3011E-04	8.6743E-03
84	3.27455E 00	6.2409E-04	6.6919E-03
85	3.51119E 00	4.1197E-04	5.0790E-03
86	3.76493E 00	2.6713E-04	3.7866E-03
87	4.03702E 00	1.6990E-04	2.7689E-03
88	4.32876E 00	1.0592E-04	1.9848E-03
89	4.64159E 00	6.4622E-05	1.3922E-03
90	4.97702E 00	3.8521E-05	9.5420E-04
91	5.33670E 00	2.2397E-05	6.3787E-04
92	5.72236E 00	1.2686E-05	4.1542E-04
93	6.13590E 00	6.9859E-06	2.6302E-04
94	6.57933E 00	3.7327E-06	1.6158E-04
95	7.05480E 00	1.9309E-06	9.6100E-05
96	7.56463E 00	9.6525E-07	5.5235E-05
97	8.11130E 00	4.6509E-07	3.0600E-05
98	8.69749E 00	2.1545E-07	1.6298E-05
99	9.32603E 00	9.5680E-08	8.3217E-06
100	10.00000E 00	4.0629E-08	4.0629E-06

216 LINES OUTPUT THIS JOB.

A N N E X 2

Evaluation of the self-absorption factor of Rh^{104} from the corresponding theoretical β energy spectrum

A.2.1. Determination of the theoretical β energy spectrum [A 1 and A 2]

For an allowed transition, the repartition of the energies of a β spectrum can be derived from the law :

$$N(p)\,dp = K.G(\pm Z, \Sigma)\, p \,.\, \Sigma\,(\Sigma_0 - \Sigma)^2\, dp$$

where :

p = particle momentum

Σ = energy of the β particle expressed in relativistic units

Σ_0 = maximum energy of the spectrum

Z = atomic number of the daughter

$G(\pm Z, \Sigma)$ = Fermi function

$$p = (\Sigma^2 - 1)^{1/2}$$

$$\Sigma = \frac{E}{0.512} + 1$$

$G(\pm Z, \Sigma)$ is tabulated in function of $\frac{p}{Z}$ [A 2]

K is a complex factor whose absolute value is not necessary for the specific case considered where the only important term is the statistic factor $\Sigma\,(\Sigma_0 - \Sigma)^2$ which is representative of the shape of the spectrum.

After integration it follows :

$$N = K' \cdot G(\pm Z, \Sigma) \cdot p \cdot \Sigma (\Sigma_o - \Sigma)^2$$

In the specific case of rhodium we have :

E max. = 2.44 Mev

Z of the daughter = 46

$$\Sigma_o = \frac{E}{0.512} + 1 = 5.765$$

It is possible to plot a theoretical spectrum, similar to the true spectrum except for the K' coefficient. The calculated values are tabulated in Table I and the corresponding spectrum has been plotted in Fig. I.

A.2.2. Evaluation of the self-absorption factor by energy groups

From the preceding values it becomes possible to calculate a self-absorption factor in assimilating the spectrum to a sum of rectangles each of which corresponding to a mean energy value and a mean number of particles (proportional to the true number by K').
By successive applications of the formula :

$$f = \frac{\lambda}{a} \left[0.5 - F_2 \left(\frac{a}{\lambda} \right) \right]$$

a good approximation of K_2, extended to the whole spectrum, can be obtained.

For a spectrum assimilated to a sum of 10 rectangles where the mean data are those of Table I the calculation, indicated in Table II, leads to :

$$K_2 = \frac{\sum_1^{10} N f}{\sum_1^{10} N} = 0.41$$

E (MeV)	Σ	$p=(\Sigma^2-1)^{1/2}$	$\frac{P}{z}=\frac{P}{46}$	G ($\pm z, \Sigma$)	$\Sigma_o - \Sigma$	$(\Sigma_o - \Sigma)^2$	N.K'
2.44(E_{max})	5.765(Σ_o)				0		0
2.138	5.527	5.44	0.1182		0.238	0.056	7.10
2.074	5.05	4.95	0.1076		0.715	0.511	53.90
1.830	4.574	4.46	0.0969		1.191	1.418	122.07
1.586	4.097	3.96	0.0860		1.668	2.782	191.14
1.342	3.621	3.48	0.0756	4.22	2.144	4.596	244.36
1.098	3.144	2.98	0.0647		2.621	6.869	271.58
0.854	2.667	2.47	0.0537		3.098	9.597	266.70
0.610	2.191	1.95	0.0424		3.574	12.773	230.26
0.366	1.714	1.39	0.0302		4.051	16.410	164.92
0.122	1.238	0.73	0.0158		4.527	20.493	78.08
0		0					0

TABLE I - Determination of the theoretical β spectrum of Rhodium 104.

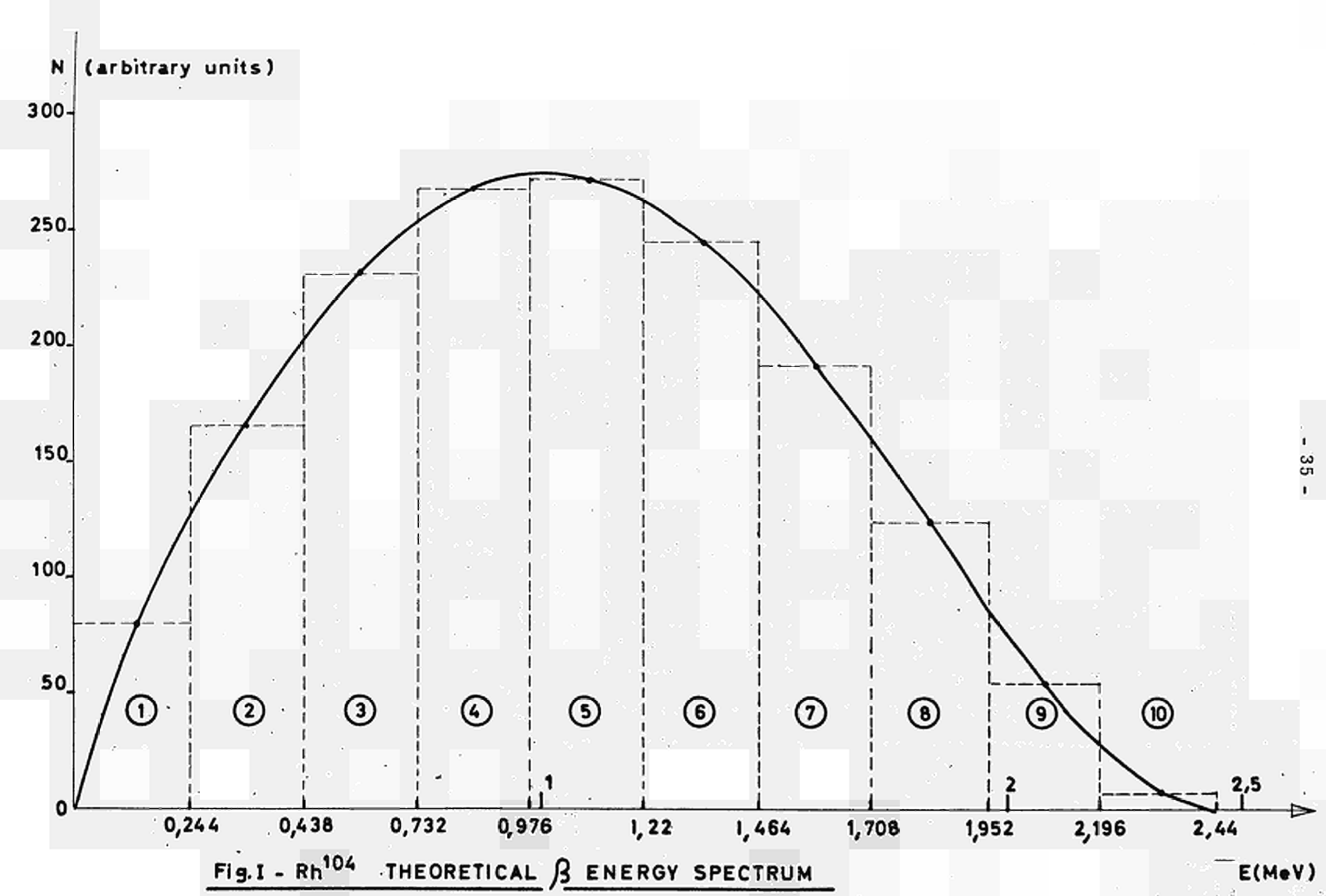

Fig.I - Rh^{104} THEORETICAL β ENERGY SPECTRUM

	N° of corresponding rectangle (see Fig.II)									
	1	2	3	4	5	6	7	8	9	10
N	781	1649	2303	2667	2716	2444	1911	1221	539	71
E	0.122	0.366	0.610	0.854	1.098	1.342	1.586	1.830	2.074	2.318
λ cm	0	0.004	0.014	0.026	0.035	0.046	0.057	0.068	0.078	0.088
λ_a		0.16	0.56	1.04	1.42	1.84	2.28	2.72	3.12	3.52
$\frac{a}{\lambda_a}$		6.2	1.78	0.96	0.70	0.54	0.43	0.37	0.32	0.28
$F_2(\frac{a}{\lambda_a})$		$2.6.10^{-4}$	0.04	0.12	0.16	0.21	0.25	0.27	0.29	0.31
f		0.08	0.26	0.40	0.48	0.53	0.57	0.63	0.66	0.67
Nf	0	132	599	1067	1304	1295	1089	769	356	47

TABLE II - Computation of the self-absorption factor from the β spectrum

$$K_2 \simeq \frac{\sum_1^{10} N.f}{\sum_1^{10} N} = \frac{6.658}{16.302} = 0.41$$

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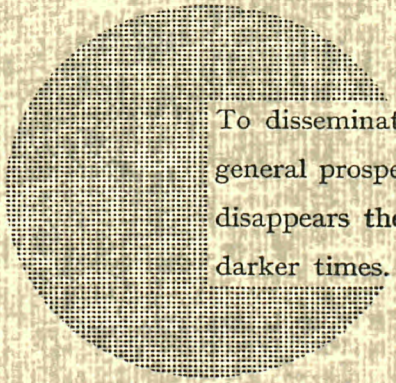

To disseminate knowledge is to disseminate prosperity — I mean general prosperity and not individual riches — and with prosperity disappears the greater part of the evil which is our heritage from darker times.

Alfred Nobel

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