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An Absolute Calibration Technique for Spontaneous Fission Sources*

M.S. Zucker
Brookhaven National Laboratory

E. Karpf
Suffolk County Community College

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ABSTRACT

An absolute calibration technique for a spontaneously fissioning nuclide (which involves no arbitrary parameters) allows unique determination of the detector efficiency for that nuclide, hence of the fission source strength.

Summary

A "neutron multiplicity counter" circuit used in conjunction with a pulse correlation circuit, knowledge of the spontaneous fission neutron emission multiplicity distribution from a source and of the values of certain parameters of the detector and electronics (die-away time, correlation time or gate width, and pre-delay) which can be independently measured, allowed an absolute calibration of the efficiency of the detector for that particular source. Since knowledge of the multiplicity distribution also gives the average neutron yield per fission, the fission rate of the source could thus be absolutely determined.

There are no arbitrary parameters in this scheme; the detector efficiency is found by matching calculations of what might be termed the "multiplicity profile" with an experimental determination. The method is illustrated using a ^{252}Cf source.

Introduction

Though a large component of the appeal of absolute calibration schemes may be purely aesthetic, there are also practical reasons for being so interested: One is forced to better understand the physical and technical aspects of the apparatus and

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the measurement process, resulting in technical or procedural improvements that would not have been realized if only an empirical approach were taken. Since there are severe restrictions on transporting nuclear materials, self-calibration or standardization, and qualification of instrumentation without such materials is useful if at all possible. Finally, as it is hoped to demonstrate here, the techniques developed may have some unsuspected utility or virtues, e.g., of precision or possibly accuracy.

A previously reported method for self-calibration[1] of instrumentation involved in assay of spontaneous fissioning material, neutron correlation counting (based on equation (11) below), required characterization of the apparatus to the same extent as the method to be reported on here; it did not require knowledge of the neutron multiplicity distribution in great detail, but did require that the detector efficiency be determined.

The present method does demand accurate knowledge of the multiplicity distribution, and also makes use of the parameters of the equipment to determine the detector efficiency unambiguously for the source being assayed. This dispenses with what is often a stumbling block for absolute calibration schemes: differences in the neutron energy spectrum of different nuclides can cause unacceptable differences in efficiency, not to mention that using a supposedly "known" neutron source to calibrate the efficiency compromises somewhat the basic principle of absolute calibration.

Description of the Method

The probability Q_n that a fission will result in n neutron produced pulses from a detector of efficiency ε for detecting single neutrons is

$$Q_n = \sum_{\nu} P_{\nu} \binom{\nu}{n} \varepsilon^n (1-\varepsilon)^{\nu-n} \qquad (1)$$

In this expression P_ν is the probability that ν neutrons are released by a given fission, and

$$\binom{\nu}{n}\varepsilon^n(1-\varepsilon)^{\nu-n} , \binom{\nu}{n}=\nu!/n!(\nu-n)!$$

is the probability that if ν neutrons were released, exactly n would be detected.

This equation may be solved for the P_ν in terms of the Q_n giving

$$P_\nu = \sum_n Q_n\binom{n}{\nu}\varepsilon^{-n}(\varepsilon-1)^{n-\nu} \quad (2)$$

where the symbols have similar meaning. These expressions, which furnish the theoretical basis of this assay method, are quite general, involving only the assumption that the efficiency is independent of the multiplicity.

The circuitry used in the assay method has the following properties: Neutron caused pulses from a well counter are processed by a circuit with the following properties: If the circuit is not occupied when a pulse arrives, a gate of prescribed time length τ is launched (after a pause $\delta \ll \tau$), such that any following pulses falling within τ are counted. Pulses which arrive during a gate cannot launch gates. A running total is kept of G (for gross), the total number of incoming pulses, and g, the number of gates launched. The number of gates, g, would equal the gross count G in the limit of the single count rate $(G/t)\to 0$ for random counts, where t is the measurement time. For finite count rates the gate duration τ acts as a classical non-updating deadtime so that the relation

$$G = g/[1-(g/t)\tau] , \text{ or } \tau = t(g^{-1}-G^{-1}) , \quad (3)$$

has been found to hold accurately over as wide a range of count rates as were involved in these measurements. The relation (3) was in fact used to experimentally determine τ. Table I lists a particular series of gross counts and the corresponding gate counts produced with a random neutron source (AmLi) placed external to the detector. Applying equation 3 to this data allows a determination of $\tau = 60.656 \pm 0.029\mu s$.

Table I. Determination of Correlation Time, τ

Gross Count* G	Gate Count* g	τ (μs)†
5,594,800	4,176,571	60.693
4,557,563	3,570,376	60.667
3,906,172	3,157,547	60.697
3,430,442	2,840,615	60.529
3,107,174	2,614,901	60.588
2,588,299	2,236,375	60.790
1,775,147	1,602,732	60.601
1,774,060	1,601,645	60.679

μ = 60.656
σ = .0808
$\sigma/\sqrt{n}$ = .0286 (n=8)

*Using a random source (Am-Li); counting time = 1000 sec.

†From $\tau = t(g^{-1} - G^{-1})$

The above circuit description will be recognized by those familiar with the history of neutron correlation counting as a now obsolete kind of circuitry used before the advent of Böhnel type circuitry.[2] The Böhnel circuitry is more efficient, since in effect every incoming pulse launches a gate, whereas in the older type of circuit a gate is launched only if there is none present when an incoming pulse arrives. A circuit of this older type, IH704A,[3] was however particularly suited to the needs of the presently discussed assay method, as it had been interfaced to another circuit, a so-called "neutron multiplicity counter"[4] (NMC), IH756, having the facility that, with the aid of external scalers, it could keep track of the number of times the gate associated with the initiating pulse would contain 0, 1, 2, 3, 4, 5, or 6 pulses. This NMC circuit was originally intended by one of the authors for P_ν measurements, but never used for that purpose.

This method for absolute calibration depends upon the fact that, for a given set of neutron multiplicities, P_ν, the set Q_n as given by equation (1), is a unique function of the efficiency ε of the detector. A given detector assaying a particular spontaneously fissioning nuclide will develop a profile Q_1, Q_2, ... which in principle can be matched up with sets of Q_n calculated theoretically from equation (1), thus effectively determining the value of the parameter ε of the detector, hence allowing an absolute determination of the amount of the particular nuclide being assayed.

The basic concept is illustrated by calculations made using equations (1) and (2) for several values of ε using a set of P_ν for ^{252}Cf:[5] Table II lists the probabilities for observing n neutrons following a single fission for various values of detector efficiency, ε=0.30,0.25,··· assuming that the finite gate width (correlation time) τ is not a limiting factor. As can be seen, the Q_n form a profile which is quite a distinctive function of the detector efficiency ε.

Table II. Q_n, Probability of Observing n Neutron Pulses Following ^{252}Cf Fission*

ν, n	$Q_n(\epsilon)$ $P_\nu(^{252}Cf)$	$Q_n(.30)$	$Q_n(.25)$	$Q_n(.20)$	$Q_n(.15)$	$Q_n(.10)$
0	.00216595	.2890532	.3619637	.4496349	.5544375	.6790411
1	.02555593	.3975073	.3995961	.3832713	.3426956	.2709487
2	.12530038	.2275392	.1842258	.1368525	.0889815	.0455370
3	.27453182	.0709125	.0464249	.0268066	.0127168	.0042253
4	.30517535	.0132939	.0070662	.0031832	.0011055	.0002392
5	.18519592	.0015698	.0006799	.0002398	.0000611	.0000086
6	.06594435	.0001187	.0000420	.0000116	.0000022	.0000002
7	.01419820	.0000056	.0000016	.0000004	.0000001	0
8	.00187802	.0000002	0	0	0	
9	.00005357	0				
10	.00000078					

*Providing there is no limitation on gate width (correlation time), τ.

There is a complication to this scheme as simply outlined above: The expression (1) makes no allowance for following pulses that fall outside of the gate and therefore will not be counted.[6] An event of a given multiplicity can register as such only if all the following pulses fall inside the gate time; in general, some will not, thus the distribution Q_n will be modified (in the direction of increasing the observation of lower multiplicities at the expense of higher order ones) from what would be calculated from equation (1). The loss of otherwise valid pulses from the gate cannot be absorbed simply by assuming a modification of ε, since (with small exceptions) those pulses falling outside of the gate will result in detector pulses that will be processed by the electronics, e.g., contributing to the gross count. The effect can be calculated accurately, however; in the following, the probability that exactly m pulses fall within a gate following a fission is derived.

Suppose $\{A\}$ represents the event "a gate occurred following a fission". Assume non-overlapping events. Then since Q_n is the probability of n pulses resulting from a fission, a gate is launched every time $n>0$. Thus the $\text{Prob}\{A\}=(1-Q_o)$. Let $\{B_m\}$ be the event "exactly m pulses fell within a gate"; then what is needed is the conditional probability of $\{B_m\}$ given $\{A\}$:

$$\text{Prob}\ \{B_m|A\} = \text{Prob}\{A\cdot B_m\}/\text{Prob}\{A\}\equiv R_m \tag{4}$$

where $\text{Prob}\{A\cdot B_m\}$ is the event that "a gate was launched and exactly m pulses fell within that time period". This is given by the probability that a gate was launched by the arrival of a group of n pulses, $n\geq 1$, with probability Q_n, followed by m of the (n-1) remaining pulses. Suppose the probability of a given pulse from a group entering the gate is p, of failing to, (1-p); then

$$\text{Prob}\{A\cdot B_m\} = \sum_{n=1} Q_n \binom{n-1}{m} p^m (1-p)^{n-m-1} , \tag{5}$$

and the probability R_m of observing m pulses under the restriction of a finite gate is

$$R_m = (1-Q_o)^{-1} \sum_{n=1} Q_n \binom{n-1}{m} p^m (1-p)^{n-m-1} \tag{6}$$

Letting τ_d be the die-away time (neutron lifetime) of the detector, τ the correlation time (effective gate width) and δ the pre-delay (time between arrival of the first pulse and the actual opening of the gate) of the correlation circuit, then since the probability per unit time of pulses from a given fission is accurately given by

$$(1/\tau_d)\exp(-t/\tau_d) \tag{7}$$

the probability of a following pulse falling within the gate time p is

$$p = (1/\tau_d) \int_{\delta}^{\delta+\tau} (-t/\tau_d)dt$$

$$= \exp(-\delta/\tau_d)[1-\exp(-\tau/\tau_d)] \tag{8}$$

If the number of gates during a given assay time is g, the expected number of pulses in the channel representing a multiplicity m is then just $N(m)=gR_m$. Table III lists for the same ε as in Table II the probability of observing exactly m pulses following a fission with the added restriction of a finite gate. Since, as will be seen below, g can easily be of the order of 10^6–10^8 for a measurement extending over a normal work day, the differences in N(m) due to the differences in the probabilities R_m can be readily seen with the statistical precision allowed in a counting experiment.

Die-Away and Pre-Delay Measurement; Apparatus Time Constant Summary

The dieaway time (neutron lifetime) τ_d for the detector was determined by varying the correlation time τ of a Böhnel type neutron correlation circuit[7]

Table III. R_m, Probability of Observing m Neutron Pulses Following ^{252}Cf Fission*
(τ_d = 91.87μs, τ = 60.656μs, δ = 4.401μs)

ν,n	$R_m(\varepsilon)$ $P_\nu(^{252}Cf)$	$R_m(.30)$	$R_m(.25)$	$R_m(.20)$	$R_m(.15)$	$R_m(.10)$
0	.00216595	.7638797	.8050129	.8456171	.8855414	.9246532
1	.02555593	.2051885	.1739413	.1412061	.1072180	.0711075
2	.12530030	.0284629	.0196611	.0124908	.0069612	.0030598
3	.22453182	.0023436	.0013269	.0006635	.0002729	.0000787
4	.30517535	.0001213	.0000565	.0000223	.0000068	.0000013
5	.18519592	.0000040	.0000015	.0000005	.0000001	0
6	.06594435	.0000001	0	0	0	
7	.01419820	0				
8	.00187802	0				
9	.00005357	0				
10	.00000078	0				

*given a gate width (correlation time) limitation.

assaying a correlated source (^{252}Cf) and fitting the correlation ("net") count N to a function of the form $N = N_0[1-\exp(-\tau/\tau_d)]$. The results of six separate determinations over a period of several days are listed in Table IV, leading to the value adopted, $\tau_d = 91.82 \pm 0.57\mu s$.(8) A typical set of experimental N vs. τ together with the calculated fit is also shown in Table IV illustrating how well the dieaway characteristic of the counter obeys simple time dependent diffusion theory.

In the IH704A, there is provision for a delay between the pulse launching a gate and the onset of the gate itself. This pre-delay is adjustable and supposed to be set so that the initiating pulse, with the shape and time duration that it leaves the amplifier, will be completely over before the gate is opened. This is so that the full width of the gate is available for any following pulses. In the present experiment it was realized only after much data had already been taken that the pre-delay actually was only 1.069μs as measured by a precision double pulse generator (BNC model 7065, resolution 1ns), whereas the amplifier pulses were ~4μs, base-to-base. The gate width was measured using the same double pulse generator to be 63.988μs. Since the effective gate width was found to be 60.656μs using the deadtime relation between gates and gross count (equation (3)), and moreover this same value gave excellent agreement with the random count rate of low multiplicity (see below), it was felt that the amplifier pulse width overshadowed the small 1.069μs pre-delay, and in fact cut into the gate in a way that produced an effective pre-delay of

$$63.988\mu s - 60.656\mu s + 1.069\mu s = 4.401\mu s$$

Thus, to summarize the parameters of this well counter and associated electronics:

$$\tau_d = 91.87 \pm 0.57\mu s, \quad \tau = 60.656 \pm .029\mu s, \quad \delta = 4.401 \pm .029\mu s.$$

Table IV. Determination of Die-Away Time, τ_d

Example: (measurement no. 3)

Measurement	fitted τ_d (μs)	τ(μs)	N Observed†	N Calculated*	Relative Differences
1	90.2852	0	—	0	—
2	93.8228	16	1970	2056	-.044
3	91.6037	32	3901	3782	+.031
4	92.4580	48	5261	5232	+.006
5	92.5326	64	6507	6450	+.009
6	90.2226	80	7415	7472	+.008
μ =	91.8208	96	8285	8331	+.006
σ =	1.4057	112	8950	9052	+.011
$\sigma/\sqrt{n}$ =	.5739	128	9748	9657	+.009

Hence τ_d = 91.82 ± 0.57μs

†counts per 100s

*from fitted parameters: N_o=12,828.9, τ_d=91.6037μs, with $N=N_o[1-\exp(-\tau/\tau_d)]$

Behavior of the NMC for a Random Source

A first order model of the count per multiplicity for a random source is to consider the probability of exactly m counts in the interval τ to be determined by a simple application of the Poisson probability. If the gross count is G in a time t, then the average count rate is G/t, so that the expected count in a gate of length τ would be $(G/t)\tau$. Hence the probability of exactly m pulses in the gate would be

$$p(m) = \frac{\langle m\rangle^m \exp\langle -m\rangle}{m!} \tag{9}$$

giving the expected count of multiplicity m for a gate count g in time t as

$$N(m) = gp(m) \tag{10}$$

A comparison of predictions from this model and observation over a range of gate count rates is shown in Table V. The agreement is seen to be excellent for m=0, fair for m=1, but rapidly becoming unacceptable for the larger multiplicities. Since $p(o)=\exp\langle -m\rangle$, a sensitive function of τ through $\langle -m\rangle$, the remarkable agreement for m=0 confirms the evaluation of τ from equation (3) and the data in the difference between gross and gate counts. On the other hand the increasing deviation for higher multiplicities shows that the above model is too simple, as judged by the agreement (seen below) between calculated and observed N(m) for a correlated source.

A more accurate model for the count rate of the NMC for a random source would be necessary for using this method to assay a source with appreciable random components. In such a case the theoretically (or experimentally) evaluated random count would have to be subtracted from the observed multiplicity distribution in order to obtain a multiplicity distribution to be compared with that predicted by equations (6) and (8). It would have to be assumed that the observed N(m) would be given by $N(m) = N(m)_{corr.} + \alpha N(m)_{uncorr.}$, with α a parameter to be adjusted for a best fit.

Table V. Comparison of Theoretical and Observed Multiplicity Frequency of Occurrence for Various Random Source Count Rates

Counts per gate	1: Gates = 4176571		2: Gates = 3557936		3: Gates = 2840615	
	Theor.†	Obs.	Theor.†	Obs.	Theor.†	Obs.
0	1974879	1962920	2701989	2687300	2306780	2296052
1	1009338	1053234	743604	767273	480197	492023
2	171227	160490	102322	95202	49990	45516
3	19365	14499	9386	6680	3468	2343
4	1642	766	645	295	180	84

Counts per gate	4: Gates = 2614901		5: Gates = 1836273		6: Gates = 1354420	
	Theor.†	Obs.	Theor.†	Obs.	Theor.†	Obs.
0	2165643	2157044	1619951	1619084	1238457	1240784
1	408242	417941	203047	208388	110850	114437
2	38478	34688	12725	11024	4960	4359
3	2417	1627	531	390	148	104
4	113	56	16	13		

*τ = 60.656μs, t = 1000s.

†from $N(m)=g\,\frac{\langle m\rangle^{m}\exp\langle -m\rangle}{m!}$, $\langle m\rangle=(G/t)\tau$

In the present instance, ^{252}Cf is known from previous work to be a nearly pure source of fission as opposed to (α,n) component neutrons. Though in the form of an oxide, the (α,n) component is overwhelmed by the spontaneous fission neutrons. Use of the formula for correlated count rate N,

$$N = \frac{1}{2}\langle\nu(\nu-1)\rangle\varepsilon^2 pq \quad , \tag{11}$$

(where q is the spontaneous fission rate and p is as from equation (8)), as an absolute calibration technique, indicates that the (α,n) component cannot be more than a few tenths of a percent.

Comparison of Observation With Calculated N(m) for ^{252}Cf

A particular ^{252}Cf source (SC6921) was studied with special thoroughness; in all, there were 21 separate determinations of the multiplicity distribution. The raw distribution data, averaged (uncorrected for background), the background, and calculations for the expected multiplicity are shown in Table VI.

The measured N(m) are displayed with the distribution deemed the best match (by eye), giving weight to the lower multiplicity frequencies as being statistically the soundest. A weighted least squares fit would be more objective, but was not considered necessary at this stage of development.

The measured values are also shown alongside of the distributions for neighboring values of ε so that the uncertainty in the determination of ε might be judged. A slight "skewness" in the fit can be noticed, in that the observed values of N(2) agree more with values of ε lower than the deemed "best" value ε = 0 189, while the observed N(3) and N(4) tend to agree more with higher values of ε. To what extent this skewness may be due to slight inaccuracies in some of the apparatus constants would have to be determined by a parameter variation study not yet done. Note that the total range of ε offered for judging the fit is only ±1.6% of

Table VI. Comparison of Observed with Calculated Neutron Multiplicity N(m)
(gross, G = 2137922±896, gates g = 1847344±645, t = 1000s)

a. Comparison with best fit

	measured distribution (raw data)	measured background distribution	measured distribution*	calculated distribution (best fit) (ε=.189)	relative error
N(0)	1579078.0±481	538.8±34.4	1578539.0±481	1578488	+.000032
N(1)	247212.0±190	5.4±1.8	247207.0±190	247227	-.000081
N(2)	19907.0±50	3.6±0.9	19903.0±50	20567	-.0331
N(3)	1059.3±7.1	2.9±1.0	1056.0±7.2	1028.8	+.026
N(4)	37.2±1.4	1.7±0.4	35.4±1.4	32.6	+.082
N(5)	3.57±0.40	1.9±0.6	1.6±0.7	0.7	+.56
	(21 values)	(7 values)			

b. Comparison with calculated neighboring distributions

	ε=.186	ε=.187	ε=.188	measured	ε=.190	ε=.191	ε=.192
N(0)	1582847	1581365	1579971	1578539	1577005	1575522	1574037
N(1)	243563	244810	245982	247207	248470	249712	250955
N(2)	19922	20140	20347	19903	20789	21013	21237
N(3)	980.1	990.5	1012	1056.4	1045.7	1062	1080
N(4)	30.6	31.2	31.9	35.5	33.3	34.1	34.8
N(5)	0.6	0.6	0.7	1.6	0.7	0.7	0.7

*corrected for background

the central value. Considering that the only free parameter in this theory is ε, all other parameters being determined by independent measurements, the agreement over several orders of magnitude of N(m) is noteworthy.

The data seem to support a value $\varepsilon = 0.189 \pm 0.002$. This is on the basis of an overall qualitative judgement of the fit. Confining attention to just N(0) and N(1), the uncertainty in ε can be narrowed down to only ± 0.001. These uncertainties at this stage of development it must be emphasized, must be considered to be of the nature of apparent precisions, not accuracies; these latter remain to be determined.

Since the gross count $G = 2{,}137{,}922 \pm 846$ per 1000s, assuming $\langle\nu\rangle = 3.757 \pm 0.10$,[9] then from $G = \langle\nu\rangle\varepsilon q$,

$$q = (2{,}137.9)/(0.189)(3.757) = 3{,}011 \text{ fissions/second.} \quad (13)$$

Using $t_{1/2} = 82.6\text{y} = 2.607\times10^9\text{s}$,[9] $\lambda = (\ln 2/t_{1/2}) = 2.659\times10^{-10}\text{s}^{-1}$. Thus there are $(3011/2.659\times10^{-9}) = 1.132\times10^{13}$ nuclei present, equivalent to a ^{252}Cf mass of $(1.132\times10^{13})(252)/6.023\times10^{23} = 4.738\times10^{-9}$g. Therefore the source SC6921 contained 0.00474μg ^{252}Cf on the assay date. Unfortunately, coming from a collection of old, poorly and even incorrectly characterized "orphan" sources, there was no independent check on this value.

Evaluation

The above method of absolute calibration in which the detector efficiency for a given source is determined by matching the multiplicity profile observed to that calculated involves no arbitrary parameters. The three apparatus or electronics parameters, τ_d, τ, and δ, are measured separately, quite independent of the "multiplicity profile" determination, and once the apparatus is thus characterized, need not be measured again. These parameters should be stable against the factors that often cause drift in electronics.

The apparent precision, particularly since no arbitrary parameters are involved, is surprisingly good considering that the procedure is still in an initial stage of development.

There is as yet no data on accuracy, but if this is comparable to the seeming precision, then the method would rival or even surpass the heretofore best available alternate techniques for fast neutron source calibration, e.g., the "manganese bath" for which the quoted accuracies are ±(2-3)%.

The time involved in calibrating a source (~8 hours) is prohibitive for routine assay, but is reasonable for a source used as a standard.

The presence of an appreciable (α,n) contribution to the neutron flux, such as would be the case of the source were $^{240}PuO_2$, would present a complication, but one which as indicated above could be overcome by either an experimental or theoretical determination of the random count. (In the present case a rather elaborate experimental evaluation of the effect of various random count rates on the NMC was made but not reported here because this was not relevant for ^{252}Cf; nor would it be for ^{238}Pu "pacemaker" type sources in which the oxide is of isotopically pure ^{16}O.)

An interesting contrast with the previously reported absolute calibration scheme involving the net count formula (equation (11)), is that whereas the present method requires accurate knowledge of the P_ν, the "net count formula" method required only a knowledge of $\langle\nu(\nu-1)\rangle$ or equivalently, Diven's parameter, $D \equiv \langle\nu(\nu-1)\rangle/\langle\nu\rangle^2$, and $\langle\nu\rangle$.

Finally, one is led to speculate that since with this method of assay a source in effect establishes its own appropriate value of detector efficiency, this assay technique may also prove to be geometry and matrix insensitive as well.

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References

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2. M.S. Zucker, "Neutron Correlation Counting for NDA, etc.", Proceedings American Nuclear Society, May 15-17, 1978.

3. IH 704A, designed by R.L. Chase, was built at BNL circa 1971.

4. IH 756, also designed by R.L. Chase and built at BNL circa 1971.

5. This set was developed by seeking a consensus among published data, as described in the paper by Zucker and Holden elsewhere in these proceedings.

6. The purpose of the finite width gate in neutron correlation counting is to increase the signal (correlated) to noise (uncorrelated) ratio; τ is usually set approximately equal to the die-away time to optimize this (S/N) ratio.

7. An obsolescent BNL developed system comprised of: an IH 773, a proportional counter pulse amplifier with 8 channels, each followed by a fast pulse discriminator, all feeding a common OR circuit, developed by L. Rogers (1972), and an IH 856, developed by D. Potter (1973), which operated with a 4 MHz clock, and was the first practical realization of the Böhnel circuit. While the IH704A could have been used for τ measurement, it offered only 4 gate values whereas the IH856 offered the 8 shown.

8. This determination was based on the nominal values listed for τ on the IH856. Measurement with a precision double pulser shows that all the nominal values should be increased by 0.488±.002μs. Thus τ_d should be 92.36μs. Since many computations had already been made and the difference was of the order of the uncertainty in τ_d, τ_d was left at 91.87μs.

9. Holden and Zucker, "^{252}Cf and ^{238}U Nuclear Parameters of Safeguards Interest", Proceedings ANS/INMM Topical Meeting on Safeguards Technology, Hilton Head, S.C., Nov. 28-Dec. 2, 1983, Transactions Am. Nucl. Soc., Vol. 45 suppl. 1, Nov. 1983.