STATISTICAL ANALYSIS OF NEUTRON EMISSION IN COLD FUSION EXPERIMENTS

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ABSTRACT

The paper discusses two techniques for studying the multiplicity spectrum of neutron emission in cold fusion experiments. In the first method the multiplicity distribution of counts in 20 ms time intervals is analysed to give information about the statistics of neutron emission in cold fusion. The results of six such experiments indicate that about 10 to 25% of the neutrons produced in cold fusion are emitted in the form of bunches 400 to 600 neutrons each. The other method discussed is an adaptation of the Artificial Dead Time method developed originally for reactor noise analysis as well as for the passive neutron assay of plutonium. An expression for the fractional loss of counts in the presence of dead time is derived. It is shown that a neutron detection efficiency of ~ 1% is adequate to estimate the average multiplicity as well as the fraction of bunched neutron emission in the presence of a Poisson background.

INTRODUCTION

Since the first announcement by Fleischmann and Pons [1] and shortly thereafter by Jones et al [2] of the observation of cold fusion reactions in palladium electrolytically loaded with deuterium, various theories and speculations have been put forward as possible mechanisms for the same. All the schemes proposed so far may be classified into two broad categories Those that lead to fusion reactions taking place one at a time i.e. wherein occurrence of one fusion reaction does not directly influence the probability of occurrence of another. In this case one can assign a certain probability per second per deuteron for the reaction rate. A figure of 10^{-20} has for example been deduced for this by Jones et al.

The second category of mechanisms leads to a cascade or sharp bursts of fusion reactions. One of the earliest speculations [3,4] attributed the cold fusion phenomenon to muon catalysis triggered by cosmic ray produced muons. It was pointed out that each muon could in principle catalyze several hundred fusion reactions within a time span of a couple of microseconds. Recently Rafelski [5] has proposed catalysis by a massive negatively charged particle X^- as being responsible for the observation of bunched neutron emission during cold fusion. Yet another mechanism proposed has been lattice crystal fracture or cracking leading to acceleration of deuterons to energies of 20 to 50 Kev in electric fields generated across fracture crevices. Such internally accelerated deuteron beams are then presumed to cause fusion reactions [6]. Here again the fusion reactions may be expected to occur erratically leading to bunched emission of neutrons. More recently coherent processes [7] have been proposed which could lead to bunched neutron emission.

Since neutrons are one of the end products of cold fusion reactions [8], it may be expected that statistical analysis such as measurement of the multiplicity spectrum of neutron emission can give valuable insight into the possible origin of cold fusion reactions. The emission of neutrons in bunches of two or more can for example be observed by employing two (or more) fast neutron detectors and looking for coincidences amongst detected pulses within a gate interval of say 1 or 10 μs. Since the average background count rate is generally small, the chance coincidence rate due to background events in such small intervals would be negligible making the task of establishing the occurrence of multiple neutron emission events quite easy.

An alternate technique of detecting fast neutron multiplicity is to employ a thermal neutron detector surrounded by a hydrogenous moderator such as paraffin. This type of detector system has the interesting property that a bunch of fast neutrons simultaneously incident on it would be temporally seperated due to the statistical nature of the neutron slowing down process and get detected as individual neutrons within a time span governed by the neutron die-away time ($1/\lambda$) in the moderator-detector assembly. It is this type of thermal neutron detector that is considered in the present studies. The pulse train issuing from such a detector can then be analysed by any of the techniques developed for the purpose in the fields of reactor noise [9] and more recently the passive neutron assay of plutonium for safeguards applications [10].

One of the most straightforward methods is to measure the frequency distribution of counts registered in short counting intervals and to relate it to the statistical characteristics of the neutron emitting source. This method was used by us to study the statistics of neutron emission from the Milton Roy commercial electrolytic cell [11] as well as some D_2 gas loaded Ti targets [12] and is described below.

STATISTICAL ANALYSIS USING PC BASED SYSTEM

Theory of Multiplicity Analysis

If the events producing neutrons are random in time and result in one neutron per event, then the number of counts observed in a time interval τ would be distributed according to the Poisson law as follows:

$$P_r = \frac{(N_0\tau)^r \, e^{-N_0\tau}}{r\,!} \qquad (1)$$

where P_r is the probability of obtaining r counts in time τ and N_0 is the average count rate. Thus when the average count rate is small i.e. when $N_0\tau \ll 1$, one can set $\exp(-N_0\tau) \sim 1$. In this case the probabilities of detecting one, two and three neutrons in the time interval τ are $(N_0\tau)$, $(N_0\tau)^2/2$ and $(N_0\tau)^3/6$ respectively. In particular note that the ratio of doubles to singles is $(N_0\tau/2)$ while that of triples to doubles is $(N_0\tau/3)$ and so on.

On the other hand if there are S_b events per second which result in emission of neutrons in bunches , say ν neutrons per bunch, then in a time interval τ which encompasses the bunched nuclear event, the probability (P_r) of obtaining r counts in time τ would be given by a binomial distribution as follows:

$$P_r = \binom{\nu}{r}(1-\varepsilon)^{\nu-r}\,\varepsilon^r \qquad (2)$$

It is presumed here that the interval τ is large compared to the neutron die-away time in the detection system. It is also assumed that the source event rate S_b is so small that only one such event occurs in the the interval τ. Here ε is the overall counting efficiency. In the limit of $\nu \gg 1$ and $\varepsilon \ll 1$ Eq. (2) simplifies to give

$$P_r = \frac{(\nu\varepsilon)^r \, e^{-\nu\varepsilon}}{r!} \qquad (3)$$

Note that while the probabilities of various multiplicities due to the random background depend on the product $(N_0\tau)$ that due to the bunched neutronic events depend mainly on ν and ε. Table I gives the expected frequency distributions of multiple neutron counts for typical values of N_0, ε, and ν. The counting time interval (τ) is kept fixed at 20 ms while the bunched neutron producing event rate (S_b) is taken as 10^{-2}/s. The data presented is for a total of 10^5 sampling time intervals. It is clear from the table that while the average count rate for Poisson events is much greater than for bunched events, the frequencies of higher count multiplicities (>2) is much larger for the bunched events. This means that if some of the cold fusion neutrons are released in bunches, it is much easier to detect these in the presence of a random background if the multiplicity distribution of counts in short time intervals is measured. Secondly, measurement of the multiplicity distribution of counts would also enable us to distinguish between the neutrons emitted in singlets and those emitted in bunches and to derive quantities like the average number of neutrons per bunch and the fraction of neutrons produced in bunches.

Let us consider a situation wherein neutrons are produced in singlets as well as in bunches. Let S_1 denote the source event rate of the former and S_b that of the latter such that $S=S_1+S_b$ represents the total source event rate. The fraction of events (f_e) that result in bunched neutron emission and the fraction of neutrons (f_n) produced in bunches can then be written as follows:

$$f_e = \frac{S_b}{S_1 + S_b} \tag{4}$$

$$f_n = \frac{\bar{\nu} S_b}{S_1 + \bar{\nu} S_b} = \frac{\nu f_e}{1 - f_e + \nu f_e} \tag{5}$$

In the situation encountered in cold fusion experiments, the product $N_0 \tau$ is small compared to unity and the product $\nu\varepsilon$ is ~ 5 as we shall see later. Thus the measured frequency distribution of counts clearly seperates into two components viz that governed by Eq. (1) and that governed by Eq.(3), thus making the task of deriving the parameters f_n and ν fairly easy. The component corresponding to single neutron emission lies in the low multiplicity region while that due to bunched neutron emission extends into the region of high multiplicities. Moreover, since the peak of the latter distribution appears at the multiplicity given by the product $\nu\varepsilon$, it is possible to deduce ν since ε can be measured using a calibrated neutron source. On the other hand f can be simply taken as the ratio of the sum of the high frequency events to the total frequency.

TABLE I

Expected Frequency Distribution of Counts for Poisson and Bunched Neutronic Events for Typical Sets of Parameters

Multiplicity of counts	Frequency of Counts in 20ms Intervals for 10^5 Samples					
	Poisson Events		Bunched Events ($S=10^{-2}$ per sec)			
			ν = 100	ν = 100	ν = 500	ν = 500
	N_0=0.3 cps	N_0=3.0 cps	ε = 0.005	ε = 0.015	ε = 0.005	ε = 0.015
			$S\nu\varepsilon$ = 0.005	$S\nu\varepsilon$ = 0.015	$S\nu\varepsilon$ = 0.025	$S\nu\varepsilon$ =0.075
0	99940	99402	99992	99984	99980	99980
1	60	597	6.1	6.6	4.00	0.07
2	$\sim 10^{-2}$	1.7	1.5	5.0	5.1	0.3
3	$\sim 10^{-5}$	$\sim 10^{-2}$	0.2	2.5	4.2	0.8
4	$\sim 10^{-9}$	$\sim 10^{-5}$	0.03	1.0	2.6	1.5
5	$\sim 10^{-13}$	$\sim 10^{-8}$	0.003	0.33	1.3	2.2

Neutron Counts Data Acquisition System

Neutrons from the cold fusion source were counted by a bank of thermal neutron detectors embedded in a paraffin moderator block. One bank comprised of three BF_3 counters, while the other was made up of three He^3 counters. The neutron die-away time in each of these was ~25 μs. The BF_3 bank was mounted close to the Milton Roy Pd-Ni electrolytic cell [11] and the He^3 bank near a D_2 gas loading apparatus [12] about 1.5 m^2 away. While one counter was being used as signal counter in one experiment the other bank served as background monitor and vice versa. The efficiency (ϵ) of detection for the cold fusion source neutrons was typically in the range of 0.5% to 1.5% depending on the exact distance between the cold fusion source and the detector assembly as well as the pulse height discriminator bias setting.

The outputs of both these counter banks were fed to scalers whose readings could be read off by a Personal Computer (PC) at the end of each counting interval which was controlled by the clock in the PC. By taking the difference in the scaler readings corresponding to the end of two consecutive counting intervals the number of counts recorded in a given counting interval is computed and stored by the PC. It took the PC typically about 280 ms to carry out these operations following each sampling time. Hence a set of 1000 samples consumed a real time of~~5 minutes. From such data accumulated over several hours, the frequency distribution of counts recorded in 20 ms intervals could be computed.

Multiplicity Spectrum Measurements and Results

To begin with the statistics of background counts was studied to ensure that the equipment was functioning satisfactorily. For this purpose all potential cold fusion sources were removed from the room where the detectors were located. Data acquisition of background counts continued in an uninturrupted manner for 63 hours over a week end (from 1800 hrs on Friday 2nd June to 0900 hrs Monday 5th June, 1989). During this run the average background count rate in the BF_3 bank was ~0.023 cps and in the He^3 bank ~0.43 cps. Table II presents the results of the frequency distribution of counts obtained in this long background run. It is heartening to note that, as expected on the basis of Poisson distribution, not even once out of the ~750,000 odd samples were 3 or more counts registered by either of the detector banks. The ratio of doubles to singles frequency further conforms to Poisson statistics, indicating that the equipment was functioning properly. Sparking in any of the counters for example would have given rise to significant non-Poisson behaviour.

Table III represents the results of our first attempt to measure multiplicity distribution of neutrons from an electrolytic cell. The data was accumulated overnight (1805 hrs on 26th May to 0645 hrs on 27th May) with the BF_3 bank viewing the Milton Roy cell which was quiescent i.e. the cell current was not on. Besides, a plastic scintillator (NE 102A) biased to register only neutrons of energy > 9 MeV monitored cosmic ray and other background events. The first column of the table gives the probability distribution of counts of the BF_3 bank for 20 ms intervals. The average count rate works out to 5.6 cps. It is clear from the frequencies of 2s, 3s and higher

TABLE II

Frequency Distribution of Background counts in Two Detector Banks

Counting interval 20 ms
Total counting time 63 hrs

Multiplicity of counts	Frequency BF_3 Bank	Frequency He^3 Bank
0	750035	743948
1	339	6413
2	1	14
3	0	0
4-20	0	0
N_0	0.023cps	0.43cps
$N_0\tau$	$5x10^{-4}$	0.0086

TABLE III

Frequency Distribution of Counts in BF_3 Bank and Plastic Scintillator with Quiescent Milton Roy Cell

Counting period	12hrs
Counting interval	20 ms
Total number of sampling intervals	144000

Multiplicity of couts	Gross Frequency	Frequency in those samples in which plastic scintillator records a count
1	11941	114
2	2760	31
3	111	0
4	19	0
5	2	0
6	13	0
7	9	0
8	3	0
9	5	0
10	1	0
11	0	0
12	1	0
13	0	0
14	0	0
15	1	0
16	0	0

multiplicities that there is considerable contribution of non-Poisson events. The second column of the table gives the frequency distribution of the same counts data whenever there was a pulse recorded by the plastic scintillator also during a 20 ms interval. From this we conclude that only about 1% of the multiple neutron events occurring in the BF_3 bank can be attributed to cosmic ray showers.

Table IV presents the frequency distribution results of the Milton Roy cell run of 12th to 14th June, 1989. As may be seen from Fig. 1, six neutron bursts of five minutes duration each were recorded during this period, the first about 50 minutes after cell electrolysis commenced on 12th June, the second and third about an hour thereafter and the remaining three a few hours after the cell current was switched off on the evening of 14th June. During the burst phase, the count rates were in the range of ~0.5 to 1.7 cps which is about 4 to 14 times that of the background value (~0.12 cps). However it is noteworthy that in 4 out of the 6 bursts observed, count multiplicities of 2,3,4,5 and even 10 have been recorded at least once each. This type of behaviour is clearly indicative of high multiplicity neutron emission events. Throughout this run lasting several days the background counter did not record any noticable increase in count rate.

TABLE IV

Frequency Distribution of Counts for 1000 Sampling Intervals Each of 20ms During Six Periods of High Neutron Activity (Milton Roy Cell Run of 12th to 14 th June '89)

Multiplicity of counts	Frequency 12th June A	B	C	14th June D	E	F	Total (A to F) Observed	Expected
1	27	0	2	7	29	22	87	117
2	0	0	0	0	3	0	3	1
3	0	1	0	0	0	0	1	$\sim10^{-3}$
4	0	0	1	0	0	0	1	$\sim10^{-5}$
5	0	0	1	1	0	0	2	$\sim10^{-7}$
6	0	0	0	0	0	0	0	$\sim10^{-10}$
7	0	0	0	0	0	0	0	$\sim10^{-12}$
8	0	0	0	0	0	0	0	$\sim10^{-15}$
9	0	0	0	0	0	0	0	$\sim10^{-18}$
10	0	1	0	0	0	0	1	$\sim10^{-20}$

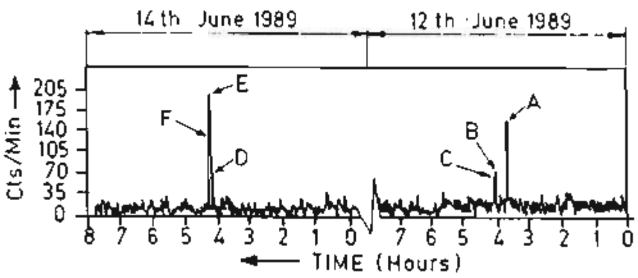

Fig.1. Neutron Bursts of Initial Part of Run Number 2 of Milton Roy Cell.

Table V summarises the frequency distribution measured during the 2.5 hour long neutron burst recorded on 16 th June, 1989 from 1900 hours onwards with the Milton Roy electrolyser. It may be noted that the cell had not been operated for the previous ~52 hours. The count rate during this wide neutron burst attained a value as high as 20 cps at the peak. The background neutron monitor which was only 1.5m away also indicated a small increase in count rate commensurate with its efficiency for neutrons emanating from the Milton Roy cell. Careful scrutiny of these results indicates that the frequency distribution essentially corresponds to a Poisson distribution. However, the fact that multiplicities of 5 or more are recorded several times again points to the sporadic occurrence of multiple neutron emission events. It is noteworthy that around 1950 hrs (close to the peak) there were more than 20 such high multiplicity cascade events within a time span of 5 minutes.

Table V

Frequency distribution of count for 1000 Sampling Intervals of 20ms Each During Periods of High Neutron Activity (Milton Roy Cell Run of 16 th June)

Multiplicity of countsf	Frequency													Total(A to L)	
	A	B	C	D	E	F	G	H	I	J	K	L	M	Observed	Expected
1	124	54	335	320	243	315	295	492	447	104	355	345	24	3429	3166
2	21	9	54	82	13	35	24	51	42	13	49	99	7	492	616
3	4	1	7	10	4	3	0	3	2	4	1	16	3	55	80
4	1	0	2	0	0	1	1	2	1	0	1	2	3	11	8
5	0	0	1	0	1	0	0	0	1	0	0	0	2	3	0.6
6	0	0	0	0	0	0	0	0	1	1	1	0	1	3	0.03
7	0	0	0	0	0	0	0	0	0	0	0	0	1	0	$\sim 10^{-3}$
8	0	0	0	0	0	0	0	0	0	0	0	0	1	0	$\sim 10^{-4}$
9	0	0	0	0	0	0	0	0	0	0	0	1	1	1	$\sim 10^{-6}$
10	0	0	0	0	0	0	0	0	0	0	0	0	1	0	$\sim 10^{-7}$
11	0	0	0	0	0	0	0	0	1	0	0	0	2	1	$\sim 10^{-8}$
12	0	0	0	0	0	0	0	0	0	0	0	0	2	0	$\sim 10^{-10}$
13	0	0	0	0	0	0	0	0	1	0	0	0	1	1	$\sim 10^{-11}$
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$\sim 10^{-13}$
15	0	0	0	0	0	0	0	0	0	0	0	0	5	0	$\sim 10^{-14}$
16	0	0	0	0	0	0	0	0	0	0	0	0	2	0	$\sim 10^{-16}$
17	1	0	0	0	0	0	0	0	0	0	0	0	1	0	$\sim 10^{-18}$
18	1	0	0	0	0	0	0	0	0	0	0	0	1	0	$\sim 10^{-20}$
19	1	0	0	0	0	0	0	0	0	0	0	0	1	0	$\sim 10^{-21}$
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$\sim 10^{-22}$

TABLE VI

Frequency Distribution of Counts
from Deuterated Zr Ti Sponge
Counting Interval 20 ms

Multiplicity of counts	Frequency BF_3 background	Frequency He^3 signal
0	67778	67493
1	281	557
2	5	11
3	0	5
4	0	2
5	0	0
6	0	0

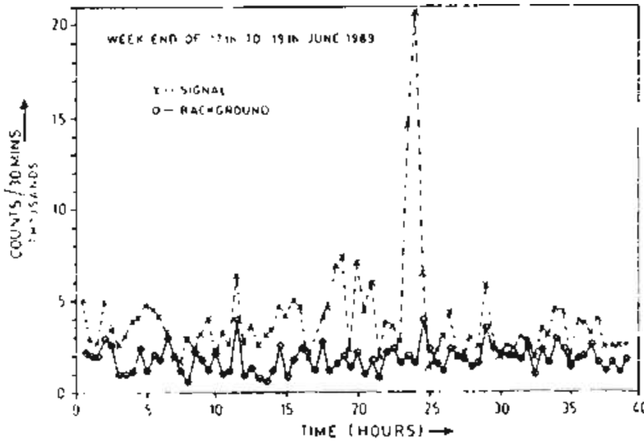

Fig.2. Neutron Output from a Deuterated Ti Disc.

Tables VI & VII summarise the results of multiplicity distribution measurements carried out with two D_2 gas loaded Ti targets. During the weekend run of 9th to 11th June, 1989 with 15 grams of Ti-Zr deuteride (see Table VI) the average count rate measured was only 0.42 cps. Since this corresponds to an $(N_0\tau)$ value of 0.008, we expect a doubles to singles ratio of 0.004 only. While the relatively high doubles events in both the background and the signal counter could possibly be attributed to statistics, or cosmic ray induced events the 3s and 4s in the He^3 detector viewing the target can only be attributed to high multiplicity neutron emissions in the deuterated Ti- Zr target. Absence of such high multiplicity events in the background channel further strengthens this conjecture. Table VII presents a similar result from a D_2 loaded Ti disc target. As may be seen from Fig. 2, the neutron active phase of this target lasted almost 85 minutes during which it is estimated to have emitted 5×10^5 neutrons in all. On the whole this target also points to the occurrence of a significant number of high multiplicity neutron emission events.

The last columns of Tables IV, V and VII give the total frequency distribution for the entire duration i.e. the sum of all the columns. Also shown are the theoretical frequency distributions expected on the basis of Poisson statistics. It is worth noting that except for the background case (Table II), in all the cold fusion measurements the observed frequencies fall according to the Poisson law for low multiplicity events but there is a distinct tendency for them to show a slight peak between the multiplicities of 4 and 6. If we assume that this peak is due to the superposition of bunched neutronic events on a Poisson background, we deduce the value of ν to be in the range of 400 to 600 since the peak of the

Table VII

Frequency Distribution of Counts from a Deuterated Disc for 1000 Sampling Intervals of 20 ms Each During Periods of High Neutronic Activity

Multiplicity of counts	Frequency A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	Total (A to Q) Obs.	Total (A to Q) Exp.
1	11	9	7	8	4	9	0	20	32	50	36	37	42	26	38	33	23	385	440
2	0	0	0	0	0	0	1	0	1	1	0	0	2	1	2	2	0	10	6
3	0	1	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	3	0.05
4	0	0	1	1	0	0	1	0	0	0	0	0	1	0	0	0	0	4	10^{-4}
5	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	2	10^{-6}
6	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	2	10^{-8}

binomial distribution occurs at the multiplicity value of the product $\nu\varepsilon$ and ε values in the experiment are typically ~0.01. Further, since the expected frequency of high multiplicities is given by $S_b \tau J$, where J is the total number of sampling intervals, we deduce that the average source event rate S_b for such events during the neutron emitting phase is very roughly about 10^{-2} per second.

In summary the multiplicity distribution of counts in 20 ms intervals has so far been measured six times during cold fusion experiments. While the background displays strictly Poisson behaviour, in the three experiments where distinct excess over background was recorded, between 10 and 25% of the neutrons appear to display high multiplicity characteristics. The observed frequency distributions can be explained as being due to bunched neutronic events superposed over a Poissonian background. Such occasional neutron bursts resulting in several hundred neutrons have also been observed by Menlove [13].

The duration of the counting interval selected viz ~20 ms was a compromise between the total volume of data required to be stored and the time resolution. Ideally the counting interval should have been of the order of the neutron die-away time in the moderator detector assembly to ascertain whether the "neutron bunches" are spread out over the entire 20 ms interval duration or whether they are in fact emitted in micro second time scales. Better time resolution is therefore called for and one of the simplest techniques, for achieving this, viz the artificial dead time method [14-15] is described in the following section.

THE ARTIFICIAL DEAD TIME METHOD

This technique was first introduced by Jacquesson [14] for estimation of the fraction of Pu^{240} in a sample and independently by Srinivasan [15] for measuring α the prompt neutron decay constant of a reactor assembly. It has since been developed as into field unit for nondestructive assay of plutonium [16]. In its simplest form the method consists of feeding the pulse train from a detector monitoring the test source to two scalers in parallel. While the pulses reach the first scaler directly, they are filtered through an artificial dead time unit before being fed to the second scaler. In this process the second scaler records a count rate lower than the first as some of the counts are lost during the dead time. In what follows we derive an expression [17] for the dead time filterd count rate and show how it is possible to distinguish between random Poisson events and bunched events and to deduce therefrom the fraction f_n of neutrons emitted in bunches.

Theory

We assume that during each counting time interval employed, the source event rate S for production of neutrons (be it in singlets or in multiplets) does not vary with time and can be described as a stationary Poisson process. It is then permissible to use the formula derived in [18] for the count rate as a function of dead time. It was shown there that in the presence of a dead time of the extendable type the observed count rate N_d is given by

$$N_d = \left\{ S \sum_{r=0}^{\infty} \frac{(-1)^r \varepsilon^{r+1}}{(r+1)!} M_{r+1} \left(1 - e^{-\lambda d} \right)^r \right\}$$

$$\exp\left[S \sum_{r=1}^{\infty} \frac{(-1)^r \varepsilon^r}{r!} M_r \left\{ \sum_{l=1}^{r} (-1)^l \binom{r}{l} \left(\left(\frac{1}{r} - \frac{1}{l}\right) e^{-l\lambda d} + \frac{1}{l} \right) + \lambda d + \frac{1}{r} \right\} \right] \quad (6)$$

where ε is the detection efficiency, M_r the r th factorial moment of the multiplicity distribution of source neutrons, λ the inverse of the neutron die-away time and d the artificial dead time introduced. In the kind of situation encountered in cold fusion experiments, the count rates are rather small compared to λ ($1/\lambda$ is typically 25-60 μs). Hence the argument of the exponential (in square brackets) is very small and the exponential may be set equal to unity. Moreover, if we choose the dead time d such that $\lambda d > 3$, the above expression reduces to

$$N_d = S\varepsilon M_1 - \frac{S\varepsilon^2 M_2}{2!} + \frac{S\varepsilon^3 M_3}{3!} - \cdots \quad (7a)$$

or

$$\frac{N_d}{N_0} = 1 - \frac{\varepsilon M_2}{2! M_1} + \frac{\varepsilon^2 M_3}{3! M_1} - \cdots \quad (7b)$$

where we have written N_0 for $S\varepsilon\nu$, the count rate in the absence of dead time.

The factorial moments M_ν can now be written in terms of the individual source event rates S_1 and S_b and the factorial moments of the multiplicity distribution of bunched neutron emision viz $\bar{\nu}$, $\overline{\nu(\nu-1)}$ etc. as follows:

$$M_1 = \frac{S_1 + \bar{\nu} S_b}{S_1 + S_b} = 1 - f_e + \nu f_e \quad (8a)$$

$$M_2 = \frac{\overline{\nu(\nu-1)} S_b}{S_1 + S_b} = \overline{\nu(\nu-1)} f_e \quad (8b)$$

$$M_3 = \frac{\overline{\nu(\nu-1)(\nu-2)} S_b}{S_1 + S_b} = \overline{\nu(\nu-1)(\nu-2)} f_e \quad (8c)$$

As noted earlier, f_e represents the fraction of events that result in neutron bunches. Eq. (7b) can then be rewritten as follows

$$\frac{N_d}{N_0} = 1 - \frac{\varepsilon \overline{\nu(\nu-1)} f_e}{2!(1-f_e+\bar{\nu} f_e)} + \frac{\varepsilon^2 \overline{\nu(\nu-1)(\nu-2)} f_e}{3!(1-f_e+\bar{\nu} f_e)} - \cdots \quad (9)$$

or

$$\left[1 - \frac{N_d}{N_0}\right] = \left(\frac{f_e}{1-f_e+\bar{\nu} f_e}\right)\left[\frac{\varepsilon \overline{\nu(\nu-1)}}{2!} - \frac{\varepsilon^2 \overline{\nu(\nu-1)(\nu-2)}}{3!} + \cdots\right] \quad (10)$$

If $\bar{\nu} \gg 1$ it may be permissible to approximate $\overline{\nu(\nu-1)}$, $\overline{\nu(\nu-1)(\nu-2)}$ etc by $\bar{\nu}^2$, $\bar{\nu}^3$ etc. Writing simply ν instead of $\bar{\nu}$ and summing the resulting power series we get

$$\left[1 - \frac{N_d}{N_0}\right] = f_n \left[1 - \frac{1 - e^{-\nu\varepsilon}}{\nu\varepsilon}\right] \quad (11)$$

It is clear from Eq. (11) that the fractional loss of counts $[1-N_d/N_0]$, which represents the deviation from Poisson behaviour, is a product of two factors : the first being f_n, the fraction of neutrons that are emitted in bunches and the second being dependent on the product $\nu\varepsilon$. Interestingly, the dependence on $\nu\varepsilon$ is similar to the dependence of the variance/mean ratio (of reactor noise theory) on the product αt. The fractional loss of counts increases with all the three parameters viz f_n, ν and ε. In Fig. 3 we show the variation of the fractional loss of counts $[1-N_d/N_0]$ with the product $\nu\varepsilon$ for various values of f_n.

In the above derivation it was assumed that the dead time introduced is of the extendable type. However under the conditions prevailing in cold fusion experiments, viz a count rate that is very small compared to λ and $\lambda d > 3$, it turns out that Eq. (11) is valid irrespective of whether the dead time is of the extendable or the non-extendable type.

Discussion

It is clear that by simply using two scalers one without any dead time and the other with an artificial dead time filter of ~50-100 μs it is possible to distinguish between the two kinds of events. Since the fraction of neutrons which are emitted in bunches in cold fusion experiments appears to be in the region of 0.1 to 0.25, the magnitude of the product $\nu\varepsilon$ required to give measureable values of fractional count loss (> 0.05) can be seen from Fig. 3 to be about 3.0. Since ν in these experiments is found to be about 400 - 600 neutrons, we conclude that an efficiency in the region of ~ 1 (which is easy to achieve) should be adequate to give measurable results. The method has the advantages of simplicity but the amount of information

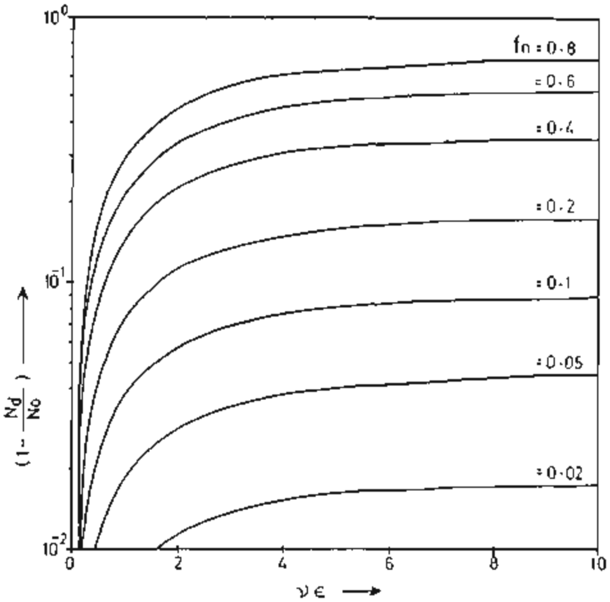

Fig.3. Variation of $(1-N_d/N_o)$ with $\nu\epsilon$

available is less than that from a full multiplicity spectrum measurement, since only two quantities viz N_0 and N_d are measured and therefore it is not possible to uniquely derive either f_n or ν. This is in contrast to the passive neutron assay problem where it is possible to derive the spontaneous fission rate and (α,n) rate even with two measurements because there the multiplicity distribution of spontaneous fission neutron emission is well known. However by conducting the experiment with two different values of the detection efficiency ϵ, it should be possible to derive both the parameters ν and ϵ. The choice of the two values of ϵ should be such that while one results in a fractional count loss comparable to f_n the other gives about half this value.

REFERENCES

1. M. Fleischmann and S. Pons, "Electrochemically Induced Nuclear Fusion of Deuterium", J. Electroanal. Chem. 261, 301 (1989)
2. S.E. Jones et al, "Observation of Cold Nuclear Fusion in Condensed Matter", Nature 338, 737 (1989)
3. M.W. Guinan, G.F. Chapline and R.W. Moir "Catalysis of Deuterium Fusion in Metal Hydrides by Cosmic Ray Muons", UCRL preprint 100881 (1989)
4. Report on the Workshop on Cold Fusion held at Santa Fe, Mexico, USA during May 1989, Science News, June 3, (1989)
5. J. Rafelski et al, "Nuclear Reactions Catalyzed by a Massive Negatively Charged Particle" To appear in Fus. Tech. (1989)
6. T. Takeda and T. Takizuka, "Fractofusion Mechanism", J. Phys. Soc of Japan, 58, 3073 (1989)
7. P.L. Hagelstein, "Status Report on Cold Fusion Theory" Proc. 1 st Annual Conf. on Cold Fusion, Salt Lake City, Utah (1990)
8. P.K.Iyengar and M.Srinivasan, "Overview of BARC Studies in Cold Fusion", Proc. 1 st Annual Conf. on Cold Fusion, Salt Lake City, Utah, (1990)
9. R.E.Uhrig, "Random Noise Techniques in Nuclear Reactor Systems", Ronald Press, New York (1970)
10. N.Ensslin, M.L. Evans, H.O. Menlove, and J.E.Swansen, "Neutron Coincidence Counters for Plutonium Measurement", Nucl. Mat. Mgmnt. Summer Isuue (1978)
11. M.S. Krishnan et al. "Cold Fusion Experiments Using a commercial Pd-Ni Electrolyser", To appear in Fusion Tech. (Aug. 1990)
12. V.S. Srikande and K.C. Mittal, "Deuteration of Titanium Targets for Cold Fusion Experiments" To appear in Fusion Tech. (Aug. 1990)
13. H. Menlove, "High Sensitivity Measurements of Neutron Emission from Ti Metal in Pressurised D_2 gas" Proc. 1 st Annual Conf. on Cold Fusion, Salt Lake City, Utah (1990)
14. J.Jacquesson J. Phys 24 Suppl to No. 1 112-116A (1963)
15. M. Srinivasan, "On the Measurement of α by a Simple Dead Time Method", Nucleonik 10, 224 (1967)
16. G. Birkhoff, L. Bondar and N. Coppo, Report EUR-4801e (1972)
17. S.B. Degweker and M. Srinivasan, "A Simple Dead Time Method for Measuring the Fraction of Bunched Neutronic Emission in Cold Fusion Experiments", Submitted for publication to Ann. Nucl. Energy (1990))
18. S.B.Degweker, "Effect of Deadtime on the Statistics of Time Correlated Pulses: Application to the Passive Neutron Assay Problem",Ann.Nucl. Energ. 16, 409 (1989)