

# NEW RESULTS ON COLD NUCLEAR FUSION: A REVIEW OF THE CONFERENCE ON ANOMALOUS NUCLEAR EFFECTS IN DEUTERIUM/SOLID SYSTEMS, PROVO, UTAH, OCTOBER 22-24, 1990

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## INTRODUCTION

A conference entitled "Anomalous Nuclear Effects in Deuterium/Solid Systems," organized by the Electric Power Research Institute (EPRI), the U.S. Department of Energy, and Brigham Young University (BYU) was held October 22-24, 1990, at BYU in Provo, Utah. It was not by accident that BYU was chosen as the venue for the conference on cold nuclear fusion (CNF). It was there that 1½ yr earlier Jones et al. first discovered (independently of Fleischmann and Pons) neutron emission following the loading of crystal lattices of the transition metals palladium and titanium with deuterium. Thus started the "cold nuclear fusion era."

The Provo conference subtitle, "Review of International Progress," was reflected in its participants. Slightly more than 150 participants from 18 countries of the Americas, Europe, and Asia were somewhat too large a group for an effective workshop. The conference aroused a great deal of interest and surpassed the expectations of the organizers, who had planned to conduct the conference within only 3 days. As a result, the conference program, which comprised >70 reports, a dozen short communications, and a visit to the BYU laboratories, proved to be overcharged. Though the sessions started at 8 am and finished at 8 to 10 pm, the conference participants clearly did not have enough time for discussions and meetings.

The main attention at the conference was on experimental work on CNF (>50 papers, including 6 on geophysical aspects of CNF and 7 on techniques). In contrast to several previous conferences on CNF that had passed in an atmosphere of agitation and exaltation, the conference in Provo was thankfully notable for its calm and efficiency. No reporters or television

staff, so characteristic of earlier CNF conferences, were present.

The conference summed up results of the 1½ yr of the cold fusion era that passed after the first reports in March 1989 that excited the whole world. During that time, CNF survived a period of unbelievable popularity, associated with hopes for a solution to the problems confronting humanity. Later on, the earlier enthusiasm changed to skepticism, irritation, and disbelief not only in energetics, but also in the reality of the phenomenon itself. The reason for this was an overwhelming flow of negative results obtained by different groups and the irreproducibility of almost all the results, which became a real curse for experiments on CNF. Another important reason for disbelief in CNF was the absence of any clear understanding of a possible mechanism for this phenomenon. It did not fit the conceptual framework of standard nuclear and solid-state physics.

The authors of this meeting summary have already written of the controversial and dramatic situation with CNF that had arisen by the beginning of 1990 (Refs. 1 and 2). What is the situation now, after the conference in Provo?

The most important conclusion following the conference is that there is now a larger body of quality evidence suggesting the reality of some kind of CNF phenomenon. However, the debate is no longer on the initial hope for implementation of a continuous "stationary" process of CNF by way of "pumping" hydrogen isotopes through a crystal lattice. Rather, the issue is one of unusual phenomena that are sporadic and that evidently have little to do with nuclear fusion in the classical understanding of this term. This change in the viewpoint was reflected in the conference name, which does not contain the usual term "cold nuclear fusion."

Confidence in the existence of CNF was felt to be somewhat more solid after the reproducibility of results had been greatly improved in a number of experiments. In some experimental series, the reproducibility of positive results was as high as 70 to 100%.

This success was due to the following factors:

1. Experiments were conducted with large samples of palladium and titanium having mass up to several hundreds of grams and surface area up to several hundreds of square centimetres, which resulted in either a larger total signal or a more frequent signal.

2. More efficient detectors (from  $10^{-6}$  to  $10^{-2}$  in the initial experiments to 30 to 45% in later ones) allowed the detection of very weak signals and rare events.

3. Thorough analysis and suppression of background was made possible through the use of materials free from radioactive impurities, employment of both passive and active protection from external noise, and work in underground low-background laboratories, even in a submarine in experiments by Argentine physicists.

4. Confidence in the positive results is enhanced by the fact that many of the data have been reproduced under different conditions and with the use of quite different techniques.

5. Some of the success of the latest experiments was due to the use of different methods for CNF stimulation (effect of pulse current, thermo- and cryoshocks, "explosive desorption," etc).

Following are the most interesting experimental results submitted to the conference, considered in greater detail. Theoretical papers, worthy of special discussion, are mentioned briefly.

## NEUTRON DETECTION EXPERIMENTS

We start with the reports that were most numerous, those dealing with neutron detection.

The group from the Los Alamos National Laboratory<sup>3</sup> (LANL) and BYU (Ref. 4) continued their research in loading titanium with deuterium from the gas phase. Since April 1990, the experiments have been conducted with modified instrumentation and an improved procedure for sample preparation. The detector used consisted of two separate rings with 9 and 42 <sup>3</sup>He-filled neutron counters, respectively, having a total efficiency of ~44% for <sup>252</sup>Cf 2.3-MeV neutrons. Background monitoring was conducted by three additional detectors. To reduce the background from radioactive impurities, <sup>3</sup>He tubes of stainless steel were used in some experiments. Preamplifiers, directly coupled to the base of the <sup>3</sup>He tubes, were sealed with desiccant and thoroughly screened against electrical pickup. The measurements were performed on samples of titanium, titanium-based alloys, and sponge titanium of total mass up to 300 g monitored for several weeks with multiple cryotemperature cycles.

In seven of nine bottles with D<sub>2</sub> metal samples, there was a neutron excess of 3 $\sigma$  to 9 $\sigma$  over the background from frequent small bursts (2 to 10 neutrons per 128  $\mu$ s). In an earlier experimental series<sup>5</sup> of five bottles, three had given positive results: two to four bursts of neutrons with multiplicity of 20 to 30. Figure 1a shows the distribution of bursts versus multiplicity for the earlier measurements with D<sub>2</sub>, and Fig. 1b presents a similar distribution in control experiments with H<sub>2</sub>. Of the recent nine bottles, eight gave results above 3 $\sigma$  significance, defined by summing up the measurements of minor bursts (2 to 10 neutrons) over 24-h measurement periods. Four of the nine recent

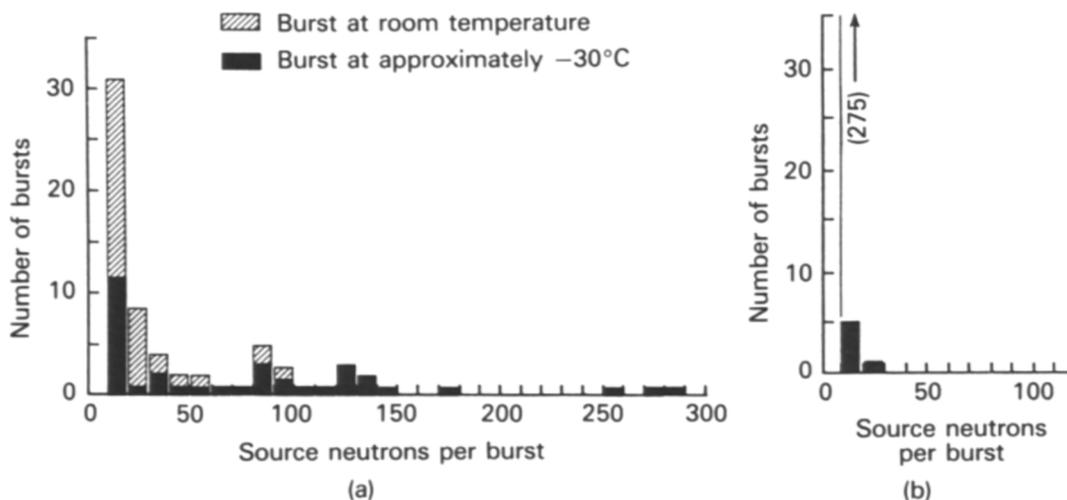


Fig. 1. Number of neutron bursts versus multiplicity: (a) deuterium runs from Ref. 5 and (b) hydrogen controls.

samples were counted with two different detectors that gave closely similar results, all above  $4\sigma$  significance (see Fig. 2). The authors point out that, as a rule, the large bursts arrived in the process of warming the samples at a temperature of about  $-30^\circ\text{C}$  (see Fig. 3), but this thermal correlation was not strongly apparent in the nine recent tests with smaller multiplicities and higher levels of deuteriding.

A few measurements made after the Provo conference have produced up to 900 coincidence neutrons, once again in correlation with warming during the cryocycle, this time in an underground tunnel at LANL. These high-statistic events gave the correct ratios of counts in the inner and outer detector rings.

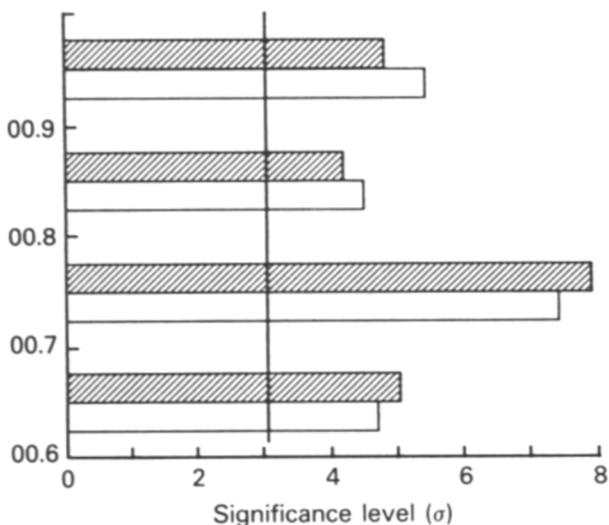


Fig. 2. Significance levels for four samples each run with two detectors.<sup>3</sup>

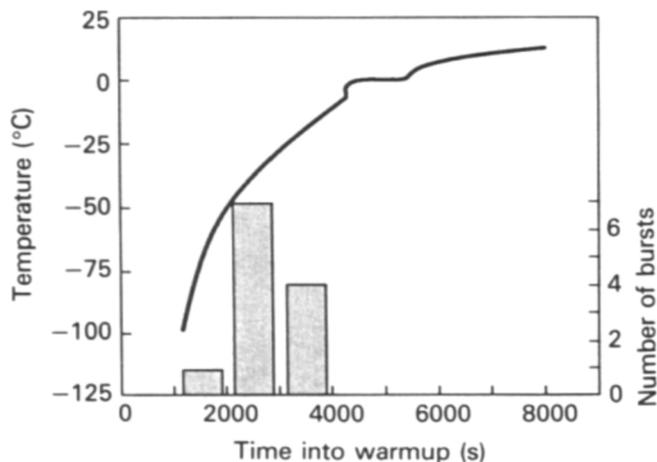


Fig. 3. Number of neutron bursts versus time and temperature.<sup>3</sup>

Jones presented the results of measurements performed by a group<sup>4</sup> from BYU, LANL, and Colorado Mountain College in the Black Cloud lead mine in Leadville, Colorado, at a depth of 600 m. Slow neutrons from palladium electrolysis were detected by a set of 16 proportional  $^3\text{He}$  counters placed into a polyethylene moderator and separated into four autonomous groups and two separate rings. The general construction and electrical screening closely resembled a Menlove-type detector. The detector total efficiency was  $\sim 34\%$ . Measurements conducted for 7 weeks showed that the single-event background (conditioned mainly by radioactive decays in the counter walls) remained stable and was  $\sim 2 \times 10^{-2} \text{ s}^{-1}$ . The background for correlated events was very low; in 3 weeks, only one background event was detected that contained two counts within  $128 \mu\text{s}$ . In the BYU laboratory, the correlated rate is a factor of 70 higher. In the mine, the cells gave periods of neutron activity from 1.5 to 40 h in duration. During 3 weeks of measurements, there were five bursts in the  $128\text{-}\mu\text{s}$  time gate, with up to 300 neutrons. An example of a burst with a high multiplicity is shown in Fig. 4.

The 300-neutron burst was produced during manual fracturing of partially deuterided YBaCuO superconductor during warming from liquid nitrogen temperature. Another of the five bursts contained 71 neutrons produced during warming of 35 g of Ti-662 alloy from liquid nitrogen temperature. More recent data included in Ref. 4 show bursts of 4, 6, and 10 neutrons in 10-s bins using a similar detector in the Kamioka mine in Japan, also from YBaCuO cryoshattering. There is only a  $5 \times 10^{-4}$  probability of these multiplicities resulting from the measured Poisson background. There was no sign that the overall neutron burst rate

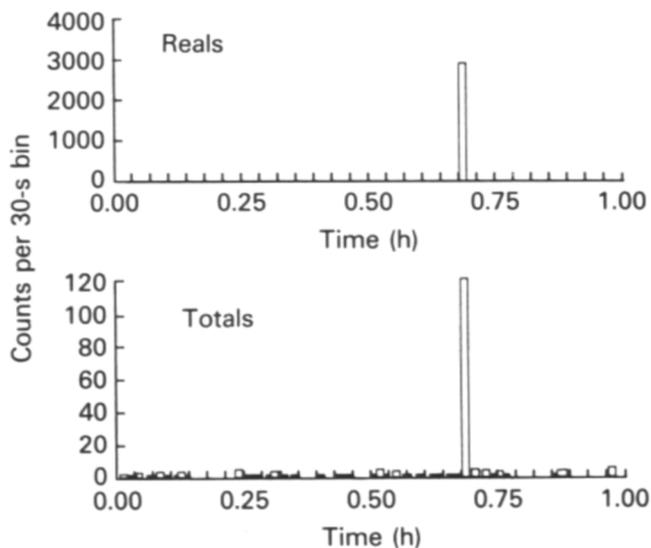


Fig. 4. A high-multiplicity neutron burst at BYU (Ref. 4).

from active samples (about two bursts in 150 h), or multiplicity, differs between surface measurements and those in deep mines.

Jones also reported<sup>4</sup> electrolytic measurements of neutron bursts (multiplicities of 35, 121, and 135) from palladium electrolytic cells with 1 M Li<sub>2</sub>SO<sub>4</sub> in D<sub>2</sub>O electrolyte in his own laboratory at BYU, during a 3-week run. A single-neutron rate of 0.08/s (source) was also quoted from these cells in one 3-h period, equal to 28 times the background or 90 $\sigma$  above background (see Fig. 5). Similar single-neutron emissions from electrolytic cells run by Wolf et al.<sup>6</sup> in the Black Cloud mine (reported later) and from Menlove's TiD<sub>x</sub> samples were noted.

In the experiments mentioned above, background checks and controls were emphasized. For example, the segmented detector was shown to be highly resistant to electronic, acoustic, and microphonic pickup. Even ingress of humidity or enormous mechanical shocks gave relations between totals and correlated

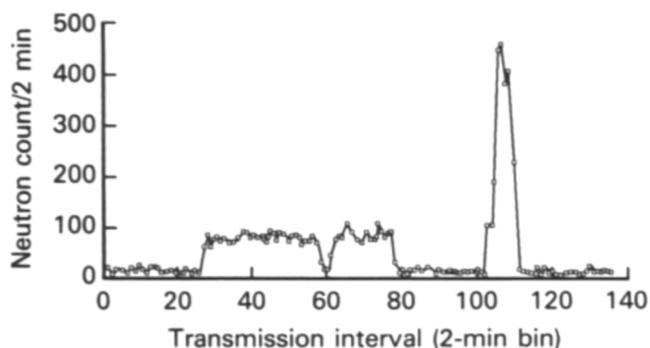


Fig. 5. A 90 $\sigma$  neutron signal from a palladium electrolytic cell.<sup>4</sup>

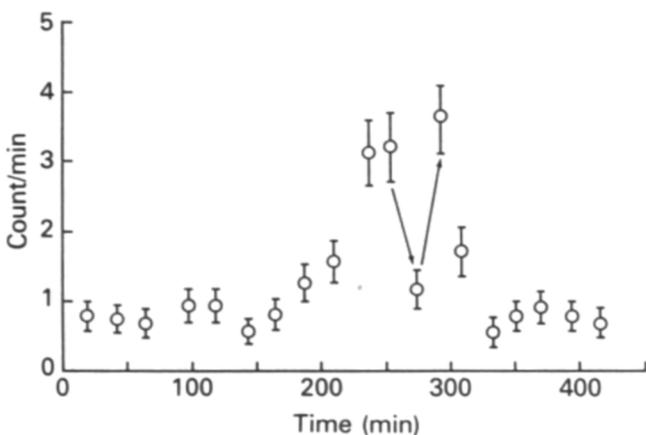


Fig. 6. Neutrons from Wolf et al.'s palladium cell at Texas A&M University using a proton-recoil detector.<sup>7</sup> The arrows show the effect of moving the cell away from the detector and back again.

counts that were in inverse relation to the signature for real neutron bursts. Equivalence among the four segments and a correct 2:1 ratio between the inner and outer rings were also demanded. Backgrounds were checked to be Poissonian with the correct theoretical and measured inner to outer ratio of 1.3:1. In the electrolytic experiments, two 4-week controls were run (H<sub>2</sub>O versus D<sub>2</sub>O cell and a D<sub>2</sub>O cell with palladium electrode outside) as well as recording concurrent backgrounds using two additional neutron detectors of diverse types. The authors underlined that the use of these measures in combination with suppression of the cosmic-ray background allowed them to substantially improve the reliability of measurements.

Wolf<sup>6</sup> (Texas A&M University) reported neutron emission from palladium electrolytic cells in an expanded effort, following his earlier report<sup>7</sup> of up to 0.8 n/s (source) (see Fig. 6) from 1 palladium sample out of 20 in three different cells. That electrode was a rod only 0.03 cm<sup>3</sup> in volume. Five new cells, each with ~0.6-cm<sup>3</sup> volume, together produced single neutrons on several occasions at 3 to 4 times the background (~7 $\sigma$ ) for periods of ~3 h, both an hour or two after starting loading at ~20 mA/cm<sup>2</sup> and also an hour or two after current density increases by a factor of 2 after appreciable loading with deuterium (see Fig. 7). The singles (source) rate was 0.5 n/s. The detection system consisted of a proton-recoil detector using two types of pulse-shape discrimination simultaneously, plastic cosmic veto detectors set to reject electronic noise pickup as well as the charged cosmic component, and a noise rejection antenna at the electronics racks. A second identical detector under the same cosmic shield with a dummy cell using the same amount of palladium and D<sub>2</sub>O and correlated event by event with the active cell detector produced simultaneous background measurements. In each case, the energy spectrum was analyzed, the active cell giving a peak as expected for 2.5-MeV neutrons but with no such structure in the background.

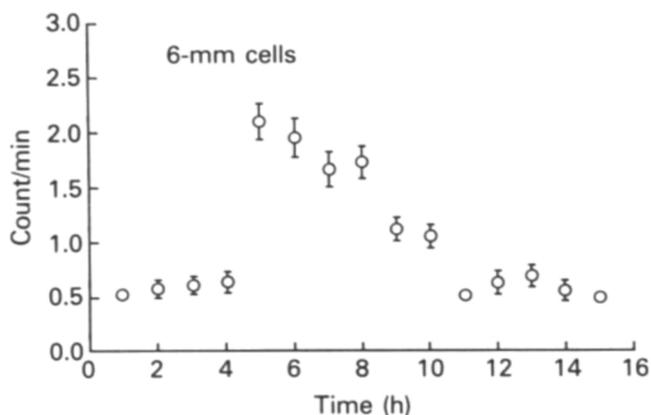


Fig. 7. Neutrons from Wolf et al.'s palladium cell in the Black Cloud mine, using a <sup>3</sup>He well detector.<sup>6</sup>

Similar results were obtained in the Black Cloud mine using a Menlove-type thermal neutron detector with just three of the five cells, giving a result of  $4\sigma$  to  $5\sigma$  significance. In this situation, the cosmic contribution was essentially eliminated as described previously, and the neutron signal appeared approximately as predicted in time and endured for about the same period as previous emissions from these cells.

Verification of the earlier results with the totally different Menlove-type detector in a different laboratory far underground adds considerably to the confidence in these measurements. Wolf also points out that his results are similar to those of Arata and Zhang<sup>8</sup> where the electrode was large, charged at low current density, and gave neutrons early in the charging [as also in the results from Bhabha Atomic Research Centre (BARC)] with signal regeneration after cleaning of the electrode surface. Experiments on signal enhancement, triggering, and scaling are continuing.

A program of studies on CNF is under way at BARC in India. During 1989 and 1990, 12 independent groups had conducted experiments with electrolytic and gaseous loading of palladium and titanium.<sup>9-11</sup> Because new results on tritium have been reported, brief mention is made of the previous neutron results from these groups so that their reports of anomalous tritium-to-neutron ratios can be seen in perspective. Although little processing was done on the neutron signals, the high signal-to-background ratios and semiquantitative agreement between different types of detectors run concurrently in some experiments made these results important during the early part of the CNF era.

In 11 different electrolytic experiments with cathodes with areas of 0.1 to 300 cm<sup>2</sup>, strong bursts of neutrons were observed. Some of these are shown in Figs. 8a, 8b, and 8c. Figure 8a shows correlation between two different types of detector; Figs. 8b and 8c show correlation between neutrons and tritium. The first bursts of neutrons (and tritium) were observed, as a rule, after a charge of several ampere-hours (from 0.6 to 3.2 A·h/cm<sup>2</sup>) had passed across a cell. Neutron emissions were also detected in experiments with D<sub>2</sub> loading from the gas phase and with subsequent thermal cycling.

The characteristic number of neutrons detected in various experiments was in the range of 10<sup>6</sup> to 10<sup>7</sup>. In most cases, neutrons were emitted for each of the targets in the form of a single high burst with intensity exceeding the background by 30 to 1000 times. After some time, the neutron emission became attenuated and stopped. It seems that, irrespective of the sample form, the integral neutron yield per unit area of the sample surface was approximately the same and in the range of 10<sup>4</sup> to 10<sup>5</sup>/cm<sup>2</sup>. The total fraction of "successful" experiments on detecting neutrons in the BARC work is ~70%. Their results are presented in Table I.

Soon after the first electrolytic experiments on

CNF were carried out in the United States, experiments were conducted in Frascati, Italy, under the direction of Scaramuzzi, with the first use of the gas-loading technique.<sup>12</sup> In that work, strong neutron bursts were detected for the first time. Such techniques have been widely practiced in more recent experiments on CNF, as described earlier.

To address the lack of reproducibility in these experiments (see Fig. 9) (as in all the others), the Frascati group performed a thorough review of their "first-generation" experiments to make sure the effects they revealed were valid. The results of this analysis and the detector performance data of the "second-generation" experiment with an improved Menlove-style, segmented detector for detecting neutrons (and with analysis for tritium) were presented at the conference.<sup>13</sup> The authors' main conclusions were as follows: (a) A critical check of the data from the initial measurements confirmed their reasonableness, and (b) in new experiments with the well detector, rare multiplicities as high as 30 were seen in the sea-level background (as noted by Menlove et al.), but in the Gran Sasso tunnel, with lower residual activity <sup>3</sup>He tubes, the total background count, integrated to 25 MeV, is 1000 times lower than at the surface.

Neutron bursts were also detected by a group from the China Institute of Atomic Energy,<sup>14</sup> who conducted some of their measurements in an underground laboratory at a depth of 580 m. Their experiments used a <sup>3</sup>He well detector with 18 tubes (20% efficiency) and a well-designed experiment sequence to attempt to verify the Menlove et al. results. The group initially found noise coincidence counts from humid air but not from microphonic pickup. Fast preamplifiers directly coupled to the <sup>3</sup>He tubes and fully screened against electronic pickup were used. Desiccant in the battery-powered high-voltage compartments as well as room temperature and humidity controls reduced the humidity so that 11 runs with H<sub>2</sub> dummy cells, mostly interspersed between cryocycles of D<sub>2</sub> runs, gave no bursts at all. Backgrounds were run for at least 2 days for each batch of material prepared.

In seven of ten cylinders filled with a mixture of titanium and D<sub>2</sub>, neutron bursts occurred at temperatures from -100°C to room temperature. In the first four cryocycles of a typical batch of material, seven bursts were observed with from 15 to 482 neutrons, which exceeded the background level (based on 1000 s) by 3 to 75 times (background was  $5 \times 10^{-3}$  coincidence/s at the surface but essentially zero at depth) (see Table II). There was a total of 23 bursts from four batches described in detail, with from 15 to 536 n/burst. As with Menlove et al.'s results, a sample would become inactive on repeated cryocycles after producing bursts in the first few cycles. Reactivation (degassing and reprocessing of chips) gave diminished frequency and intensity of bursts. This pattern of results from an independent investigation constitutes a

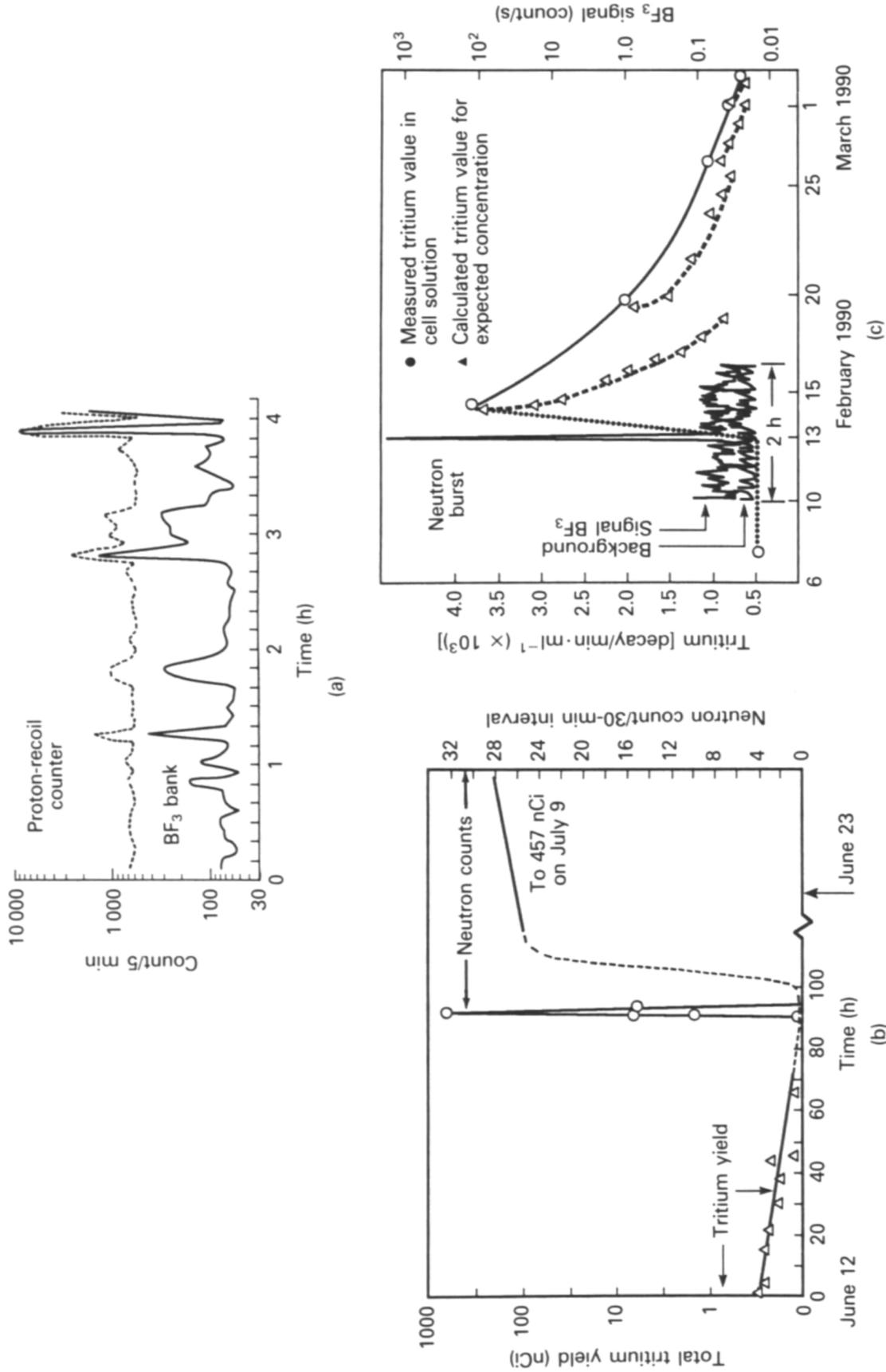


Fig. 8. Results of experiments at BARC (Ref. 9): (a) correlation between two different detectors, (b) increase in tritium yield after neutron emission during palladium electrolysis, and (c) increase in tritium yield after neutron emission during palladium electrolysis.

TABLE  
Summary of Electrolysis Experiments with

	Series				
	1	2	3	4	5
Date	May 21, 1989	April 21, 1989	June 12-16, 1989	May 5, 1989	March 15, 1990
Cathode Material Geometry Dimensions (mm) Area (cm <sup>2</sup> )	Titanium Rod 22 diam × 150 long 104	Pd-Ag Tubes 3 o.d. × 200 high 300	Pd-Ag Tubes 3 o.d. × 200 high 300	Pd-Ag Disks (5) 115 diam × 0.1 thick 78	Palladium Plate 40 × 50 × 1 thick 20
Anode	Stainless steel pipe	Nickel pipes	Nickel pipes	Porous nickel	Titanium plate
Electrolyte Volume (ml)	NaOD (5 M) 135	NaOD (5 M) 250	NaOD (5 M) 250	NaOD (5 M) 1000	NaOD (5 M) 300
Current density (mA/cm <sup>2</sup> )	≤400	~300	~300	~800	~200
Switching on Charge (A·h/cm <sup>2</sup> ) Time (h)	1.2 3	0.6 5	--- 0.5	3.2 4	0.8 4
Active life	Few hours	~3.5 h	~2 h	≤3 min	<1 min
Neutron yield Number of bursts Total n/cm <sup>2</sup>	Continuum 3 × 10 <sup>7</sup> 2.9 × 10 <sup>5</sup>	9 4 × 10 <sup>7</sup> 1.7 × 10 <sup>5</sup>	1 0.9 × 10 <sup>7</sup> 1.3 × 10 <sup>4</sup>	1 5 × 10 <sup>6</sup> 1.3 × 10 <sup>4</sup>	1 1 × 10 <sup>6</sup> 5 × 10 <sup>4</sup>
Tritium yield Total (Bq) Total (atom) t/cm <sup>2</sup>	2.6 × 10 <sup>5</sup> 1.4 × 10 <sup>14</sup> 1.3 × 10 <sup>12</sup>	1.5 × 10 <sup>7</sup> 8 × 10 <sup>15</sup> 2.7 × 10 <sup>13</sup>	3.8 × 10 <sup>6</sup> 1.9 × 10 <sup>15</sup> 6 × 10 <sup>12</sup>	7 × 10 <sup>6</sup> 4 × 10 <sup>15</sup> 10 <sup>13</sup>	--- --- ---
(n/t) ratio	2 × 10 <sup>-7</sup>	0.5 × 10 <sup>-8</sup>	0.5 × 10 <sup>-8</sup>	1.2 × 10 <sup>-9</sup>	---

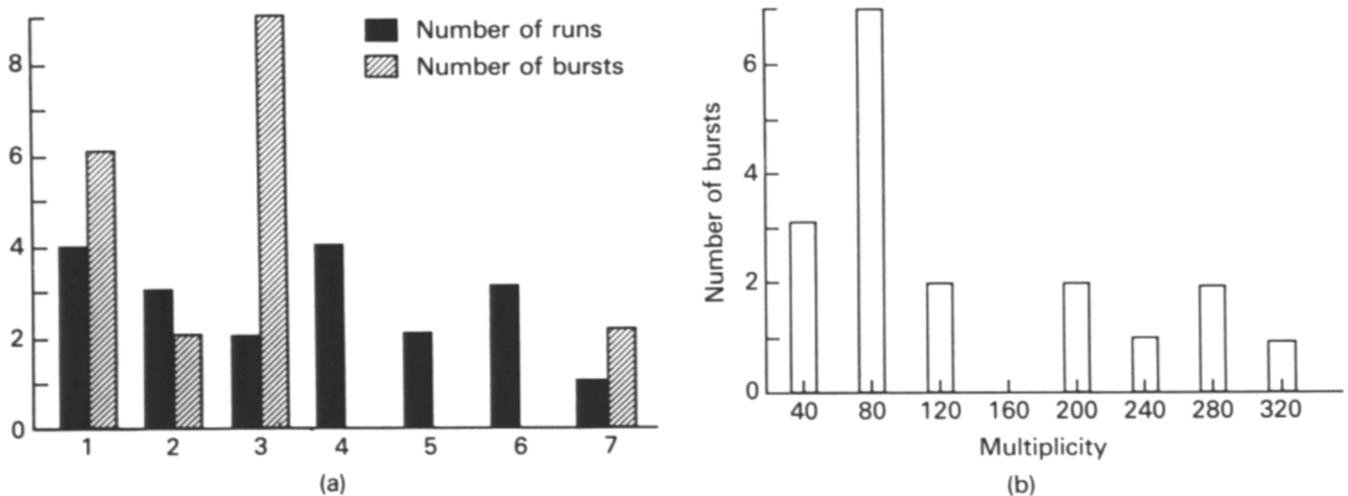


Fig. 9. Results of experiments at Frascati Research Centre: (a) number of runs and neutron bursts<sup>13</sup> and (b) number of bursts versus neutron multiplicity.

## I

## Neutron and Tritium Generation at BARC

Series					
6	7	8	9	10	11
April 21, 1989	June–August 1989	January–April 1990	July 1989	February 1990	December 1989
Palladium Hollow cylinder --- 5.9	Palladium Cube 1 cm <sup>3</sup> 6	Palladium Pellet 11 diam × 11.2 high 5.7	Palladium Ring 25 diam × 10 high × 1 thick 18	Palladium Coil 1 diam × 140 long 4.4	Palladium Button --- 8
Platinum mesh	Platinum mesh	Platinum mesh	Platinum mesh	Platinum mesh	Platinum mesh
LiOD (0.1 M) 45	LiOD (0.1 M) 150	LiOD (0.1 M) 120	LiOD (0.1 M) 250	Li <sub>2</sub> SO <sub>4</sub> (0.05 M) 140	LiOD (0.1 M) ---
≤340	~100	~700	~60	~50	<100
3.0 9	2.5 24	650 930	34 330	0.15 3	36.7 300
~5 h	~5 days	~100 s	~40 h	~5 days	8 h
3 3 × 10 <sup>6</sup> 5 × 10 <sup>5</sup>	17 1.4 × 10 <sup>6</sup> 2.3 × 10 <sup>5</sup>	1 3 × 10 <sup>6</sup> 5.2 × 10 <sup>5</sup>	Many 1.8 × 10 <sup>8</sup> 10 <sup>7</sup>	Many 5.8 × 10 <sup>6</sup> 1.3 × 10 <sup>6</sup>	2 2.4 × 10 <sup>6</sup> 3 × 10 <sup>5</sup>
1.42 × 10 <sup>5</sup> 7.2 × 10 <sup>13</sup> 1.2 × 10 <sup>13</sup>	1.3 × 10 <sup>3</sup> 6.7 × 10 <sup>11</sup> 1.1 × 10 <sup>11</sup>	7.7 × 10 <sup>3</sup> 4 × 10 <sup>12</sup> 5.2 × 10 <sup>13</sup>	325 1.8 × 10 <sup>11</sup> 1 × 10 <sup>10</sup>	32.5 1.8 × 10 <sup>10</sup> 4 × 10 <sup>9</sup>	6.3 × 10 <sup>3</sup> 3.5 × 10 <sup>12</sup> 4.4 × 10 <sup>11</sup>
4 × 10 <sup>-8</sup>	1.7 × 10 <sup>-6</sup>	10 <sup>-6</sup>	10 <sup>-3</sup>	3.2 × 10 <sup>-4</sup>	7 × 10 <sup>-7</sup>

verification of the LANL results. The same group failed to detect neutrons from palladium electrolytic cells.

A rate increase using <sup>3</sup>He detectors was also registered in electrolysis with a palladium electrode by a group<sup>15</sup> from the University La Sapienza, Italy, although the authors believe this could be due to electronic pickup or some false effects (for example, due to mechanoemission<sup>1</sup>).

Registration of bursts of gamma quanta by the Frascati group, who conducted electrolytic saturation of palladium and titanium with deuterium in the underground Gran Sasso laboratory, was reported by Celani.<sup>16</sup> The report also contained new data on the search for neutron emission following gaseous loading of high-temperature superconducting Y<sub>1</sub>Ba<sub>2</sub>Cu<sub>3</sub>O<sub>7-x</sub>-type materials with deuterium. Samples of 6 to 8 g mass were subjected to a complex series of cryo and pressure cycles. The group used <sup>3</sup>He-type detectors

with efficiency of only 0.6%. During the first thermal cycle (~1 h), neutron emission rose to ~10 counts (with background ~1 count/h, i.e., signal of 1666 n/h with a background of 166 n/h). In the subsequent cycles, the excess emission decreased and completely vanished after the tenth cycle.

Granada<sup>17</sup> (Centro Atomico Bariloche, Argentina) reported small neutron enhancements (<2 times background) as well as many negative results while current cycling palladium electrolytic cells, observed with a 22% efficient detector (18 <sup>3</sup>He tubes connected in three groups with "only 1 of 3" anticoincidence logic in a 2-μs gate). Precautions were taken against electronic and microphonic noise and humidity. Backgrounds were run with H<sub>2</sub>O but not simultaneously with D<sub>2</sub>O runs. Integrated average counts over 68 additional runs on three cells, conducted at a depth of 50 m in a conventional submarine, yielded a 40% (3σ) increase over background. The enhancements seemed

TABLE II  
Neutron Bursts from the Second Batch of Samples at the China Institute of Atomic Energy\*

Number of bottles: 3  
Material: TA1 turning  
Total amount: 270 g  
Pressure: 90 atm

Beginning Date	Time	Cycle Number	Warmup Time (h)	$R + A$	Number of Neutrons	$(n + b)/b$	$n/\sigma$
April 4-10, 1990		Background		No burst			
April 10, 1990	19:54	1	1.81	49	34	2.82	6.71
			2.36	1123	221	12.96	44.13
April 11, 1990	9:10	2	0.14	503	144	9.56	24.88
			3.47	3191	385	24.15	56.36
April 11, 1990	18:04	H <sub>2</sub> dummy		No burst			
April 12, 1990	9:30	H <sub>2</sub> dummy		No burst			
April 12, 1990	18:00	3	4.58	18	15	1.84	3.11
April 13, 1990	9:30	4	1.53	91	51	3.78	8.00
			2.92	4968	482	27.04	74.96
April 13, 1990	18:00	5		No burst			
April 14, 1990	8:50	H <sub>2</sub> dummy		No burst			
April 14, 1990	15:40	H <sub>2</sub> dummy		No burst			
April 15, 1990	9:40	6		No burst			
April 15, 1990	18:00	7		No burst			
April 16, 1990	9:40	8		No burst			
April 16, 1990	18:00	H <sub>2</sub> dummy		No burst			
April 17, 1990	9:15	H <sub>2</sub> dummy		No burst			

\*Taken from Ref. 14.

to be associated with high deuterium loading and high concentration gradients in the cathodes. The authors state that the deuterium diffusion length over the cycle time of  $\sim 90$  s would indicate only a small effective volume for nuclear reaction rate calculations.

Another interesting observation was made by a group from Weber State University.<sup>18</sup> In two experiments with deuterium gas-loaded palladium, two neutron bursts were registered in the first experiment. A rise in the neutron emission level occurred for almost 10 days in the second. No increased activity was found in a long experiment using hydrogen or in separate background runs. The bursts were highly non-Poissonian. An increase in the sample resistance was observed, as well as a pressure increase, coinciding with one of the high neutron bursts of  $\sim 3000$  n/h (source) (see Fig. 10). The possibility of such changes in conductivity, connected with the formation of unstable hydride phases, has been predicted by the Lebedev Physical Institute (LPI)-LMI group.<sup>1</sup>

Results were reported by Takahashi<sup>19</sup> (University of Osaka), who also detected neutrons in pulsed electrolysis using an NE-213 liquid scintillation spectrom-

eter with pulse-shape discrimination between neutrons and gammas, as well as a <sup>3</sup>He detector. In addition to 2.45-MeV neutrons, groups in the 3- to 7-MeV range appeared (see Fig. 11). Maximum count rates were 2 to 3 times backgrounds measured using a palladium cell with no electrolysis and a cell with no palladium.

An indication of a possible initiation of CNF reactions in chemical reactions was first obtained in experiments<sup>20</sup> conducted at the Institute of Nuclear Physics of the Academy of Sciences of the USSR at Novosibirsk. A brief communication to that effect was delivered by Danos, who visited the institute shortly before the conference. In dissolving crystals of LiD in D<sub>2</sub>O accompanied by heating up to 70 to 80°C, the neutron count rate was found to increase to  $1.70 \pm 0.14$  times background. A similar effect was discovered in exothermic interactions of deuterated complex salts of palladium and platinum with zinc. Although the appearance of neutrons from a chemical reaction is astonishing, the experiment used a Menlove-type screened detector in a low-background subterranean laboratory. The results were fairly reproducible (see Fig. 12).

Vysotskii and Kuz'min<sup>21</sup> (Kiev and Moscow State

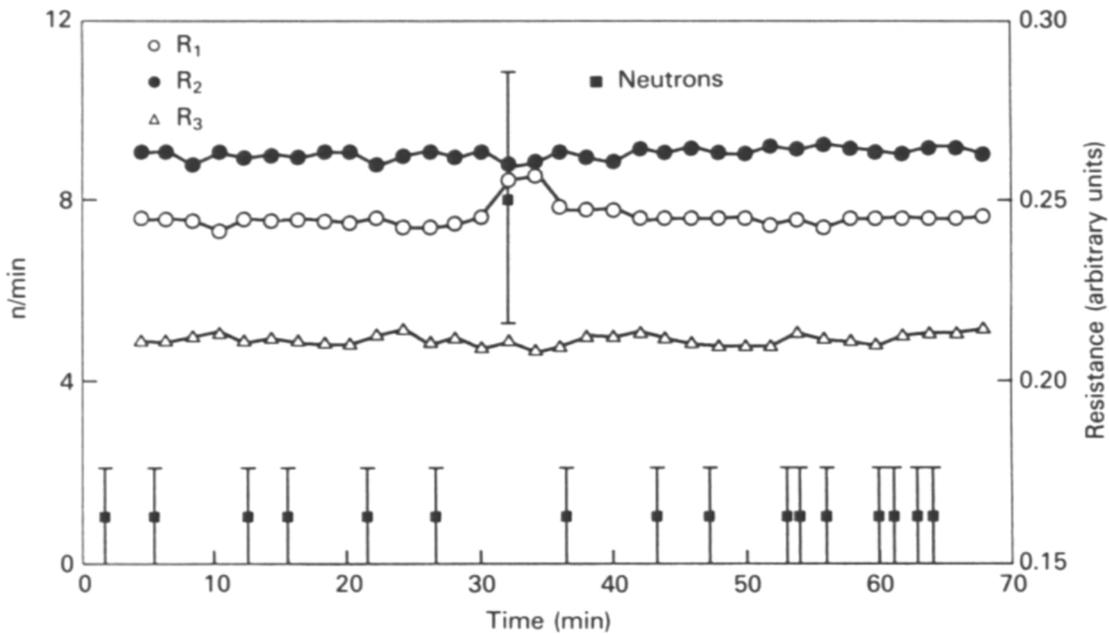


Fig. 10. Neutron count rate and resistance in the second neutron burst at Weber State University.<sup>18</sup>

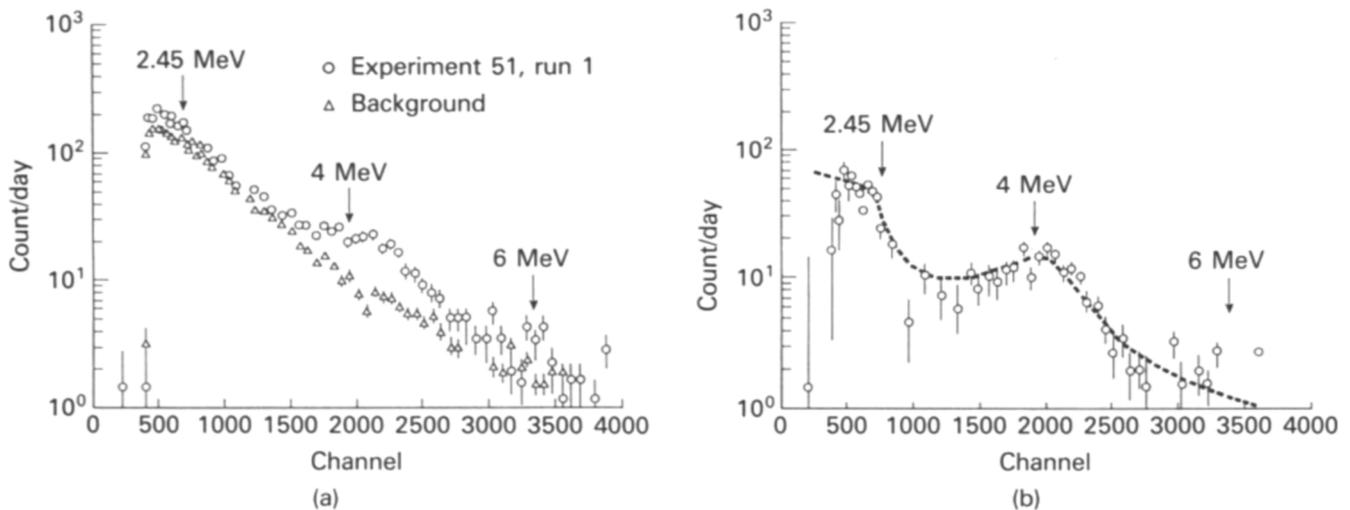


Fig. 11. Recoil-proton spectra by an NE-213 detector for experiment 51, run 1 (Ref. 19): (a) comparison of raw pulse-height spectra between foreground and background runs and (b) recoil-proton spectrum for excess neutron counts.

Universities, respectively) reported neutron emission from titanium and palladium electrolytic cells using two neutron detectors [ZnS(Ag) scintillation type and  $^3\text{He}$  tubes] with overall efficiencies of 1 to 10%. Care was taken to measure backgrounds before and after each run using the same detector as well as continuously during the runs with a similar detector 10 m away. Controls with  $\text{H}_2\text{O}$  and without any water agreed with the background, although the latter could vary by a factor of 2 from day to day. Large plate elec-

trodes gave neutron enhancements of up to 4 times background in about a dozen runs, the signals appearing soon after the start of electrolysis and often being correlated with warming or cooling of the electrolyte (see Fig. 13a). In one run involving both hydrogen and deuterium, a peak intensity of 7.5 times background was found (see Fig. 13b). Most of the neutron emissions lasted 10 to 20 min.

A group from the University of Manitoba, headed by McKee, reported<sup>23</sup> possibly anomalous emission of

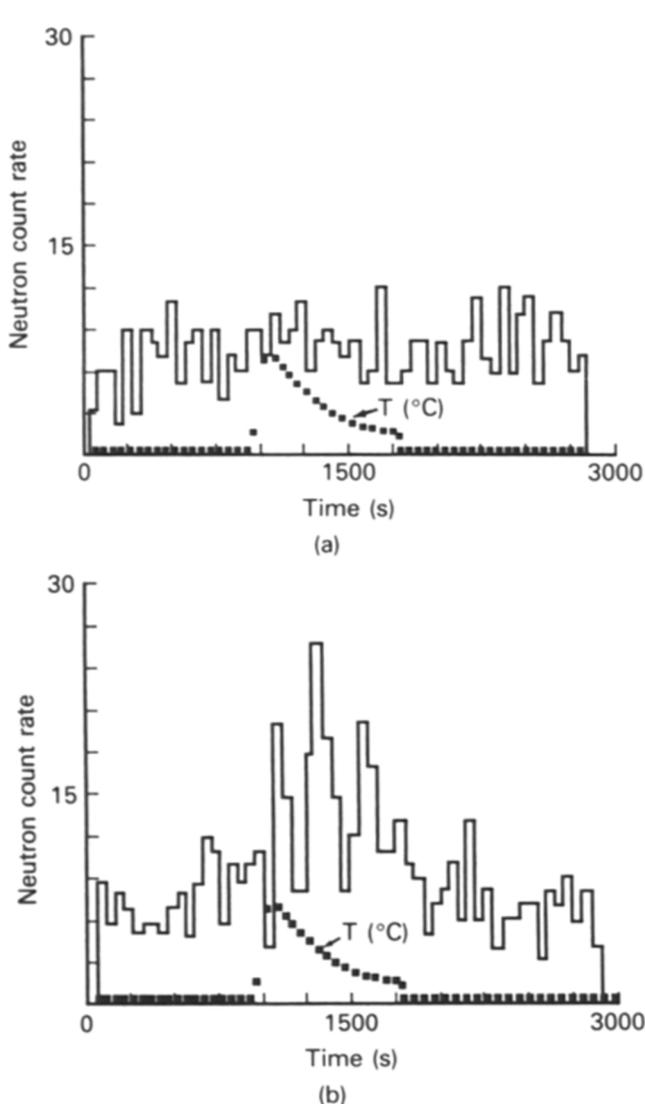


Fig. 12. Neutron count rate during redox reactions using (a) hydrogen salts and (b) deuterium salts. Elevated temperature marks the period of reaction.<sup>20</sup>

neutrons from palladium and titanium targets during implantation to very high loadings ( $\sim 2 \times 10^{31} \text{ m}^{-3}$ ) with 60-keV  $\text{D}^+$  and 30-keV  $\text{D}_2^+$ . Whether the neutrons observed were due to normal hot fusion was not resolved.

Work of the LPI-LMI-LSU group<sup>23</sup> is mainly reported under the section dealing with correlation experiments, but their neutron results are mentioned here. During the first 6 h of electrolysis (Pd/LiClO<sub>4</sub> cells with a 13-g cathode), a series of six small neutron bursts was observed, each containing 10 to 100 neutrons ( $\sim 100$  times background) and each lasting  $\sim 1$  min. Fast and slow neutron coincidences were required (within 10 to 100  $\mu\text{s}$ ). Backgrounds were run with the same materials but no current, with a nickel cathode

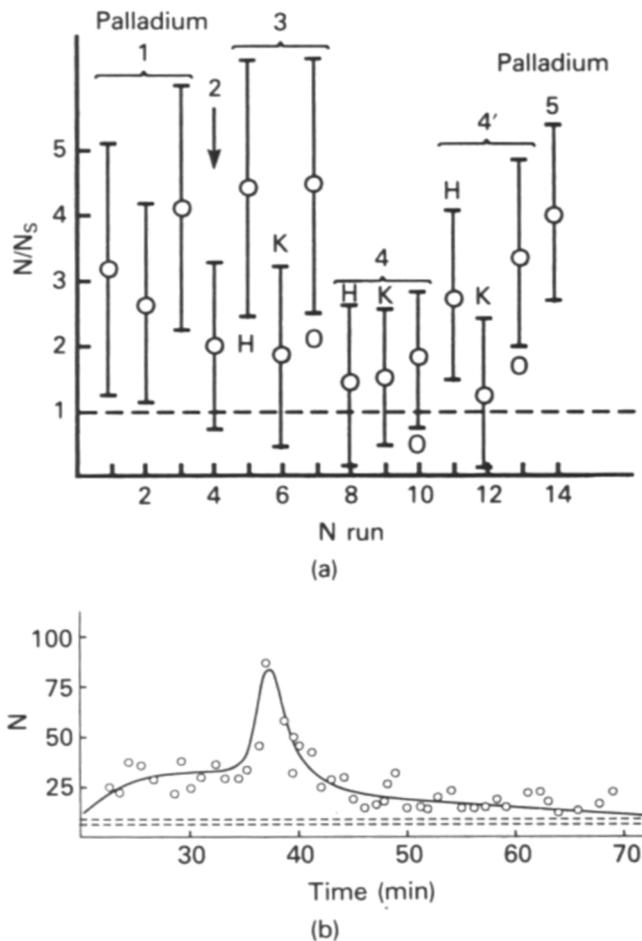


Fig. 13. (a) Neutron count ratio to background for palladium cells (runs 1, 2, 3, and 14) and titanium cells (runs 4 through 13) (Ref. 21) and (b) time trace of neutron count rate in one run.

in the same electrolyte and nickel with  $\text{H}_2\text{O}$ -based electrolyte. Other low-statistic events were reported involving triple and ternary coincidences between neutrons, protons, and acoustic and electromagnetic signals. In the Baksan underground neutrino observatory, a doubling of the neutron count rate was experienced 5 h after the start of electrolysis,<sup>24</sup> somewhat similar to the results of Jones et al. and Wolf et al. A total of 42 neutron counts were recorded in delayed coincidence with acoustic start pulses. Figure 14 shows moderating time distributions as evidence of real neutrons coming from the central cell.

Note that in the experiments conducted by the LPI-LMI-LSU group, as well as by the University of Osaka group, the Centro Atomico Bariloche group, and by the University La Sapienza group, a correlation effect with time-dependent electrolysis current, predicted earlier by the LPI-LMI group,<sup>1</sup> was observed.

Along with reports containing positive results,

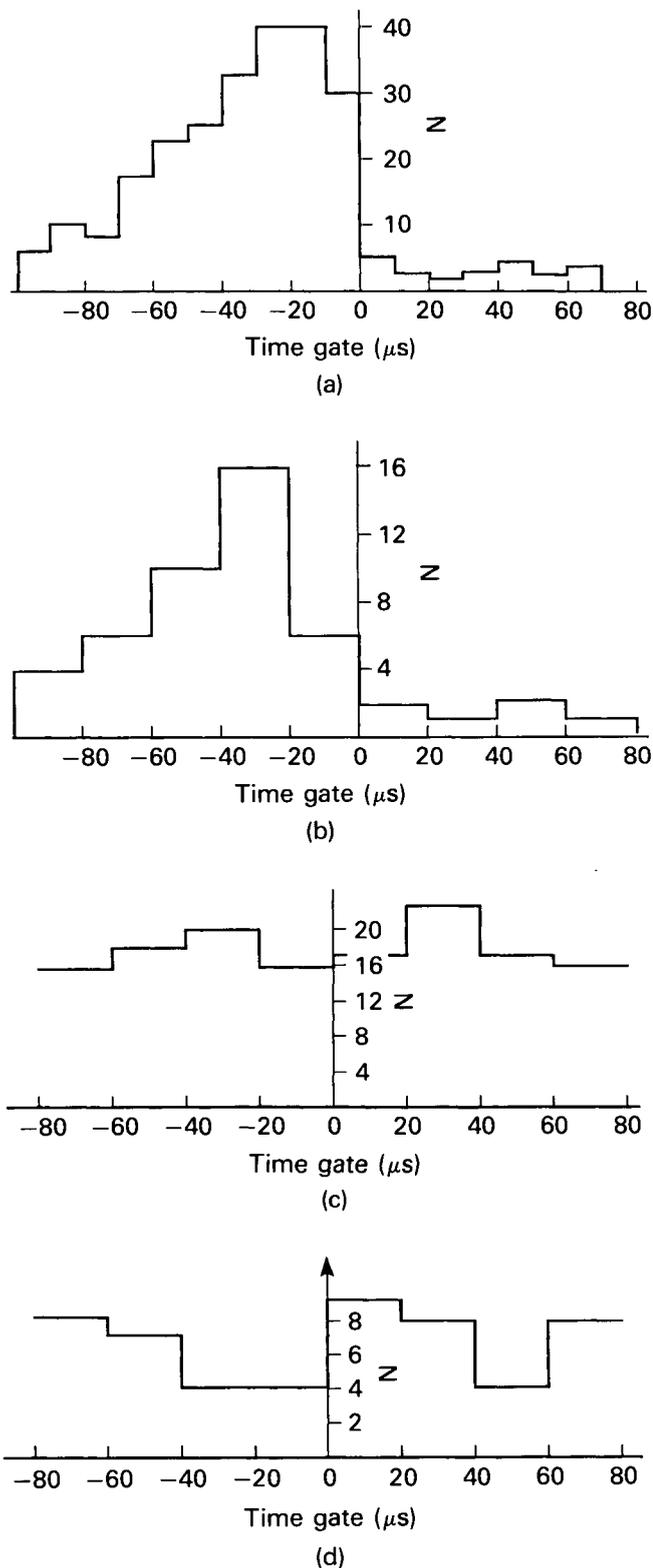


Fig. 14. Neutron moderation times (a) for  $^{252}\text{Cf}$  using proton-recoil start signal (Ref. 24) and (b) with palladium electrode and delayed acoustic start signal, (c) with start signal generated by  $^{252}\text{Cf}$  neutrons, and (d) with start signal generated by "hand."

there were four communications on experiments that failed to observe any neutron emission at all.

Anderson<sup>25</sup> (LANL) reported the results of measurements of integral neutron yield, spectroscopic measurements, and a search for neutron bursts. No excess neutrons were found either in experiments with electrolysis or with gaseous loading. A thorough comparison of neutron background performed by the authors both at ground level and in an underground room (at a 15-m depth), with empty detectors and with those having different fillings, gave results similar to the effects associated with CNF signals. In particular, in the integral neutron spectrum, fluctuations were detected at the level of  $3\sigma$  to  $7\sigma$ . In the background neutron spectrum, a weak peak was observed at an energy of  $\sim 2.5$  MeV. Additionally, some events were observed with a high neutron multiplicity (mostly  $<30$  n, but also 22 events  $>30$  n at the surface with a lead brick in the detector, compared to only 1 event underground) due to the cosmic-ray background (see Fig. 15). An important lesson of this work is the necessity of a thorough check of detector operation and background level in experiments on CNF.

A group from Oregon State University,<sup>26</sup> in the process of a 40-week electrolysis of heavy water, observed seven instances of temperature rise not accompanied by a rise of neutron intensity, gamma quanta, or tritium concentration. The authors stated that the thermal effects were caused merely by electrochemical effects.

No positive results were obtained also by a group from Eötvös University, Hungary,<sup>27</sup> who had attempted to detect excess neutrons and gamma quanta during electrolytic deuteration of the amorphous alloy  $\text{Fe}_{90}\text{Zr}_{10}$  since this alloy possesses a high hydrogen adsorptivity and had not been used previously in experiments on CNF.

Mention should also be made of negative results on neutron detection in electrolytic and gaseous charging of palladium and titanium obtained by a group<sup>28</sup> from the Joint Institute for Nuclear Research (JINR), USSR, which, however, were not reported due to the absence of the authors.

## CHARGED-PARTICLE DETECTION

As is well known, detection of energetic charged products of nuclear fusion (protons, tritons, and  $^3\text{He}$ ) in experiments on CNF is greatly hindered by the very short particle paths in both the samples and the detectors. That is why until recently there were only a handful of papers on the search for charged products of CNF, mostly containing negative results.<sup>1,2</sup> In contrast, at the conference in Provo, a surprising number of papers (seven) were presented that contained positive results on charged particles, mainly protons.

Mention should first be made of the work of Cecil

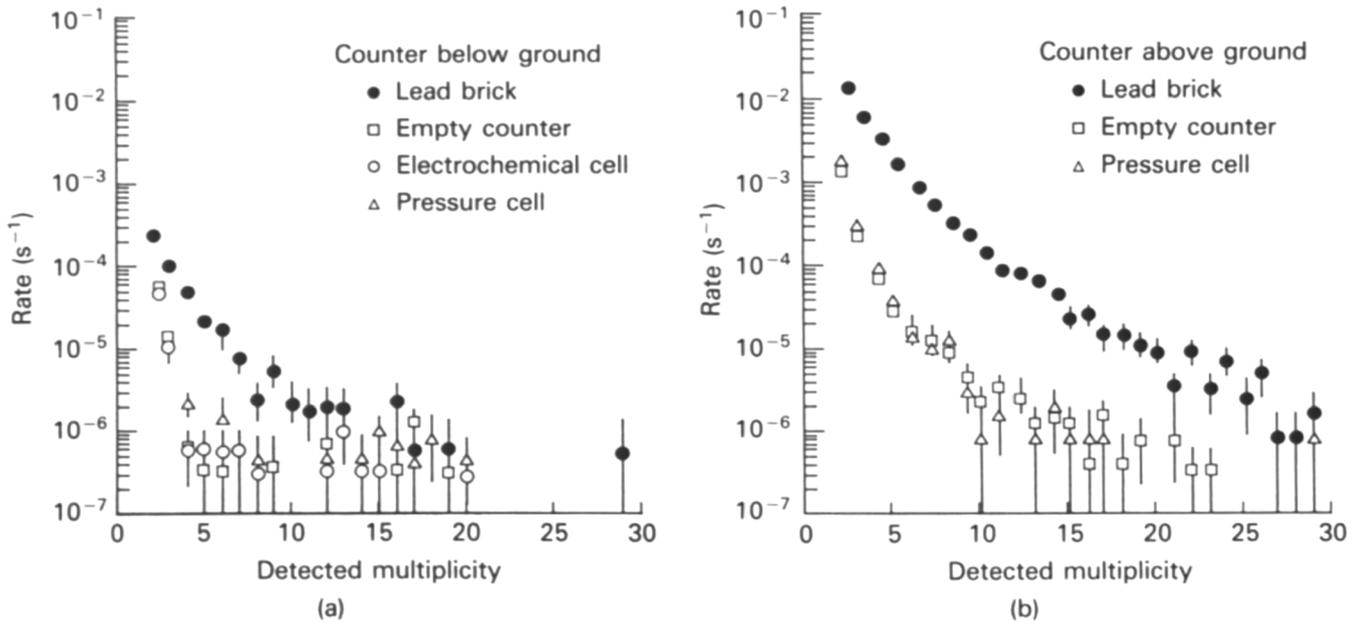


Fig. 15. High-multiplicity neutron events from Ref. 25: (a) below ground and (b) above ground.

et al.<sup>29</sup> (Colorado School of Mines), who, for the first time, observed a whole series of intense bursts of charged particles (up to  $10^3 \text{ s}^{-1}$ ) emitted from deuterated foils of Ti-662 alloy. During 56 days of measurements, 24 bursts were detected in 12 samples out of 26. The activity was initiated during thermal cycling in the range of  $-180^\circ\text{C}$  to room temperature (see Fig. 16). Measurements performed with the use of silicon surface-barrier detectors and thin aluminum degrading foils made it possible to infer that the particles were most likely tritons or  $^3\text{He}$  with a maximum energy of  $\sim 10 \text{ MeV}$ . In eight foils saturated with hydrogen, analogous bursts were not observed in 7 days of measurements. Since October 1990, however, Cecil et al. have been unable to reproduce the particle bursts.

Cecil et al.'s work was inspired by earlier reports from Chambers et al. (Naval Research Laboratory) that ion implantation of  $\sim 350\text{-eV}$  to  $1\text{-keV}$  deuterons into titanium produced rare bursts of intense charged particles. Chambers reported<sup>30</sup> that bursts of what appeared to be  $5\text{-MeV}$  tritons had appeared four times in nine experiments, at rates of the order of 10 to 30 event/s for 2 to 5 min (see Fig. 17). The spectra showed a distinct energy for each burst, with well-shaped pulses and energy peaks. One experiment with poor statistics showed a split energy peak after an energy-degrading foil was inserted to cover part of the detector aperture, with the energy loss consistent with tritons.

The Cecil et al. experiments showed similar results with higher peak rates and an apparent correlation, or triggering, using cryocooling and warming cycles, accounting, perhaps, for a larger number of shorter experiments and more particle bursts. It is interesting to

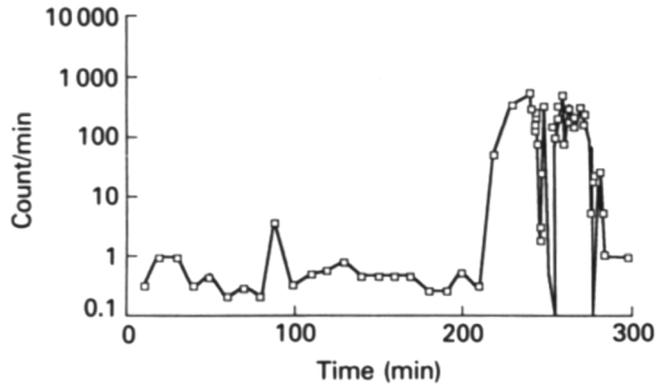


Fig. 16. Charged-particle activity over time from Ref. 29.

note that all bursts observed in Cecil et al.'s work when using the part-aperture degrading foil technique (15 bursts) produced double energy peaks (see Fig. 18). The sudden appearance and cessation of the particles in both groups' work and the good energy definition ( $\sim 600 \text{ keV}$ ) for each burst suggest a very small local site for the nuclear reactions that produced them and, therefore, reaction rates several orders of magnitude larger than the neutron emission rate published by Jones et al.

Chambers and Cecil pointed out that these two sets of experiments were not at all definitive, and, moreover, claim emission of particles at energies that cannot be accounted for at all by conventional  $d + d$  reactions. Contrary evidence was presented by Wolf. In his experiment, Wolf deuterated titanium foils specifically to

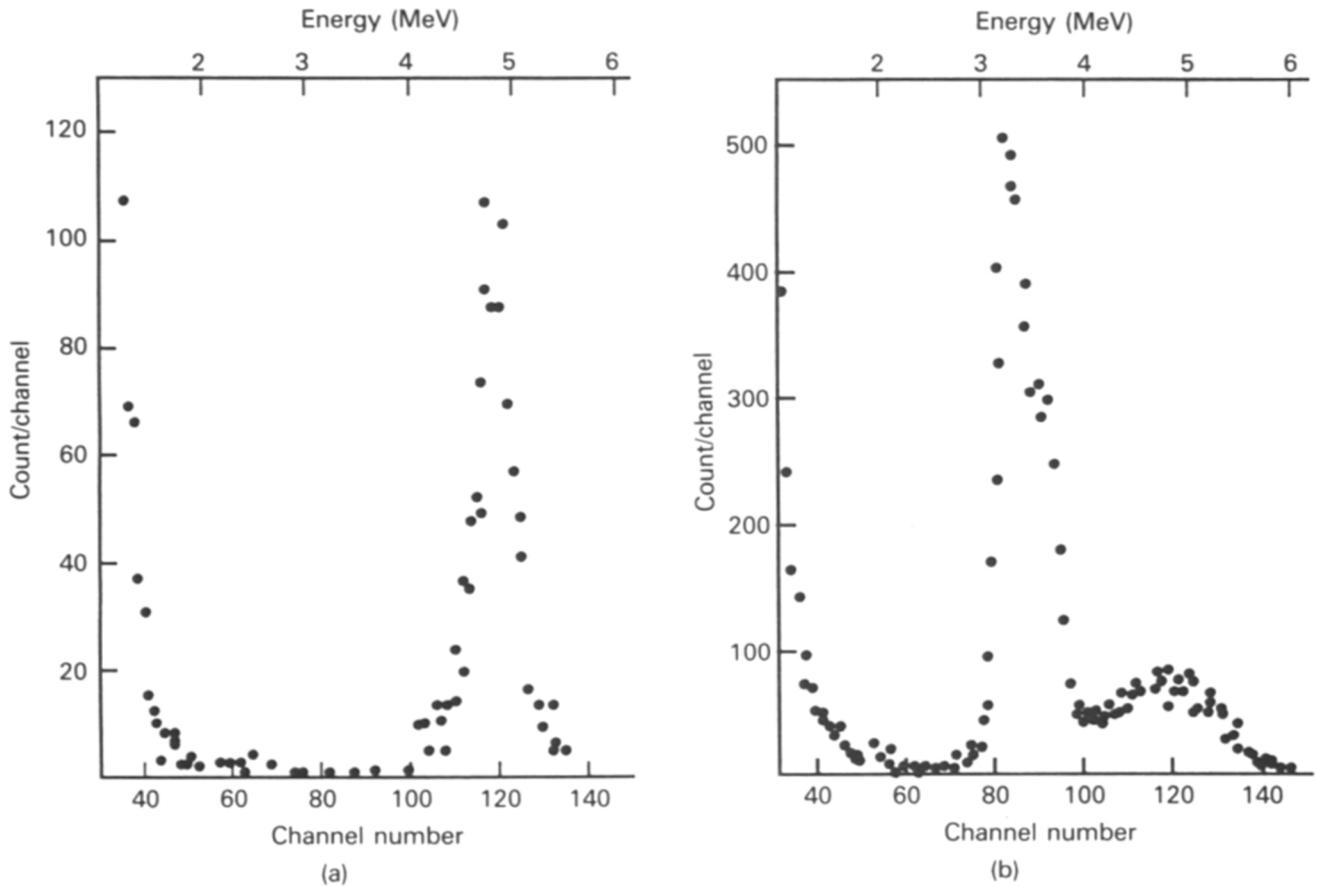


Fig. 17. (a) Spectra acquired after 40 min of 350-eV deuterium bombardment of a 1- $\mu\text{m}$ -thick titanium film evaporated onto 500 nm of gold on a 3.8- $\mu\text{m}$ -thick nickel foil. The spectral peak, centered at 5 MeV, occurred during two  $\sim 1$ -min-long bursts and consists of  $>1100$  counts. (b) Spectra acquired after 5 min of 350-eV deuterium bombardment of a 1- $\mu\text{m}$ -thick titanium film evaporated onto a 3.8- $\mu\text{m}$ -thick nickel foil during a 5-min-long burst. The double peaks are due to the changing of the detector bias voltage from  $-200$  V to zero and back to  $-200$  V again during the reaction. The spectrum consists of  $>8000$  counts.<sup>30</sup>

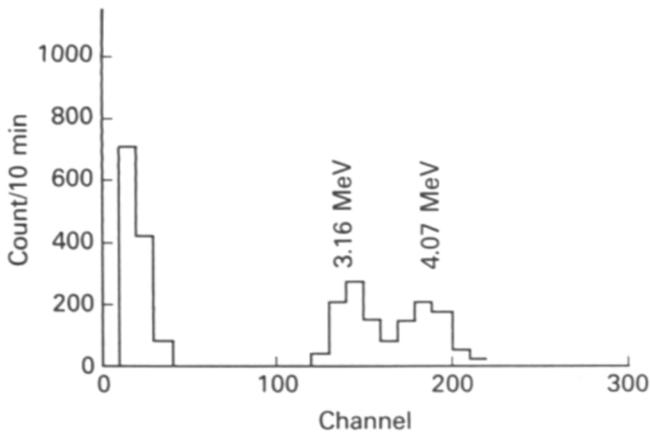


Fig. 18. Energy spectrum of charged-particle burst with energy-degrading foil over part of the detector aperture.<sup>29</sup>

imitate Cecil et al.'s procedure. The foils were placed in a high vacuum and cooled down to liquid nitrogen temperature. This was followed by a warming cycle for 24 h. In each series, two samples of  $\sim 300\text{-mm}^2$  area were used. They were viewed by silicon semiconductor detectors constituting an active, high-efficiency particle identification system. In many samples, each subjected to thermal cycling four times, no emission of single charged particles was observed. The background was defined mainly by alpha particles from radioactive decays.

Jones described<sup>31</sup> a new large-area particle detector consisting of a thin plastic scintillator bonded to a thick glass scintillator. The detector could be run in conjunction with a neutron spectrometer using a fast waveform digitizer and event storage for off-line analysis. After elimination of cosmic (anticoincidence with neutron detector) and radon decay backgrounds and

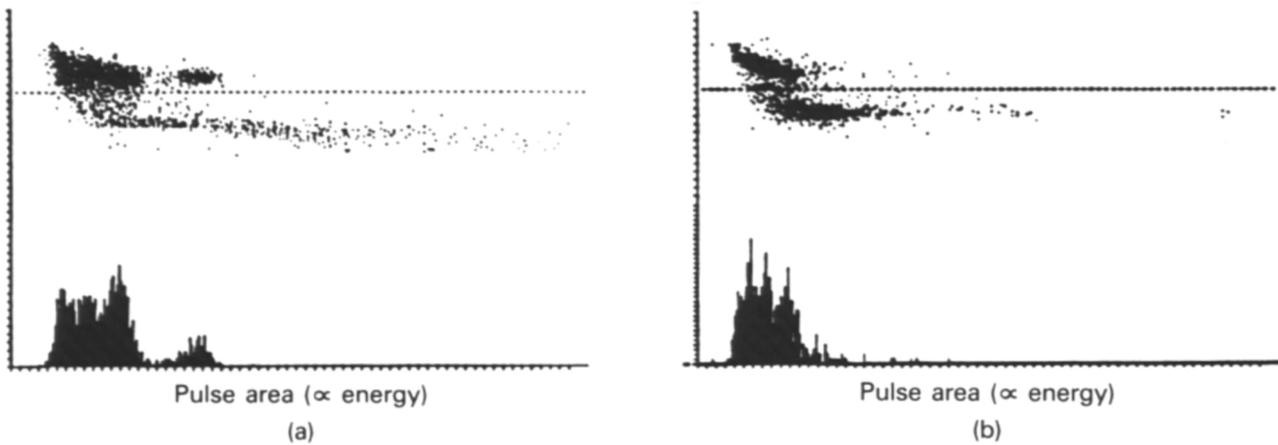


Fig. 19. Charged-particle energy spectra from Ref. 31 showing a peak in (a) the test sample that does not appear in (b) the background.<sup>31</sup>

using deuterium-charged palladium foils, several episodes of charged-particle emission were detected at rates similar to the Jones et al. neutron rate and at energies in the 2.3- to 3.0-MeV range if they were protons, to 4 MeV if deuterons or tritons, and to 8 MeV if alpha particles. The spectra show clear peaks (see Fig. 19) relatively free of background (signal-to-noise ratio was ~35). Having 1% neutron efficiency in relation to 50% particle efficiency ( $2\pi$ ) meant that any coincident neutrons could not be seen against the background at sea level. No enhancements were seen with equivalent exposures of hydrated foils or with  $TiD_x$  foils.

In the experiments of three other groups, LPI-LMI

(Ref. 23), Osaka University,<sup>19</sup> and Tsinghua University,<sup>32</sup> searches were made for correlation between proton emission and electromagnetic radiation. The group from LPI-LMI used time-varied electrolysis current to stimulate the CNF reactions. All three groups recorded emission of charged particles.

**ANALYSIS FOR TRITIUM**

Much attention at the conference was paid to experiments on the search for tritium production. The matter of tritium generation via the channel  $D + D \rightarrow T + p$  in CNF is one of the most acute and disputable.

TABLE  
Detection of Tritium During

	Experiment			
	1	2	3	4
Cathode material	Pd-Ag	Palladium	Palladium	Palladium
Surface area (cm <sup>2</sup> )	113	113	19	14.5
Electrolyte volume (ml)	150	150	150	65
Current density (mA/cm <sup>2</sup> )	350	350	105	160
Electrolysis time	12 h	30 h	13 days	7.4 days
Tritium measurements				
Initial concentration (Bq/ml)	1.44	3.33	3.6	2.7
Maximum concentration (Bq/ml)	225.7	18.5	---	$0.9 \times 10^4$
Final/initial concentration ratio	167	5.6	3.36	3425
Total excess (Bq)	$3.3 \times 10^4$	$2.3 \times 10^3$	$2.7 \times 10^3$	$6 \times 10^5$
Atoms	$1.76 \times 10^1$	$1.2 \times 10^{12}$	$1.44 \times 10^1$	$3.2 \times 10^{14}$
Yield of tritium per square centimetre	3	2	2	2
	$1.6 \times 10^{11}$	$1.1 \times 10^{10}$	$0.8 \times 10^{11}$	$2.2 \times 10^{13}$

While in many experiments, some tritium yield was discovered, which usually exceeded the neutron yield by several orders of magnitude when measured, in numerous other experiments, no tritium excess was found. The conference in Provo strengthened the position of those supporting the prevalence of the tritium channel over the neutron channel ( $D + D \rightarrow n + {}^3\text{He}$ ) but did not give a final answer to this question.

The most extensive results on tritium were obtained by groups lead by Srinivasan<sup>10</sup> (BARC) using palladium and titanium by electrolysis, by gaseous loading, and in experiments using a plasma focus device. The tritium level in the near-surface layer of the samples was measured by different methods: by direct counting of beta activity using gas proportional counters, by NaI and germanium detectors used for detection of 4.9-keV X rays from excitation of titanium atoms, and by a radiographic technique using X-ray films. In all 22 experiments with electrolytic cells, excess tritium was found in quantities of  $10^{10}$  to  $10^{16}$  atoms. An indication was obtained of a simultaneous production of neutrons and tritium in about half of the experiments, (see Figs. 8b and 8c). The integral tritium yield was in the range of  $4 \times 10^9$  to  $1.7 \times 10^{14}/\text{cm}^2$  of the sample surface. In 10 out of 22 cells, it was in the range of  $10^{12}$  to  $10^{14}/\text{cm}^2$ , whereas in the others from  $10^{10}$  to  $10^{12}/\text{cm}^2$ . Just as for neutrons, the total share of "successful" experiments with tritium detection in the BARC work was  $\sim 70\%$ . The most striking feature is the large value of the tritium-to-neutron yield ratio, which is typically  $10^6$  to  $10^9$  and only seldom  $10^3$  to  $10^4$ , the latter sometimes when the tritium assay was known to be incomplete.

An interesting result recently obtained by BARC

is connected with the use of a plasma focus facility using deuterium fill gas.<sup>33</sup> Following a run with 80 discharges,  $10^{16}$  tritium atoms were found in the surface layer of the central electrode. The authors suggest a stimulating role of high-frequency heating in generating tritium in titanium.

Table I and Tables III through V summarize the main data from previous experiments at BARC on the search for tritium. The questions aimed by critics concerning the role of ambient tritium contamination at BARC can only be answered by further experiments with careful controls.

Positive results on the search for tritium were also presented by groups from the Universidad Autonoma de Madrid,<sup>34</sup> LANL (Ref. 35), University La Sapienza,<sup>15</sup> and LPI-LML-LSU (Ref. 23). The last two groups used time-variable current in the electrolyzer to attempt stimulation of tritium production.

Claytor<sup>34</sup> (LANL) reported production of small amounts of tritium from deuterium absorbed into a device consisting of alternate thin disks of palladium and silicon, made from compressed powders. The passage of a pulsed electric current (up to 2500 V, 100 Hz, unipolar, 150- $\mu\text{s}$  width) for periods up to 500 h (typically 100 h) gave yields of up to  $7 \times 10^{12}$  atoms of tritium and one yield of  $4 \times 10^{15}$  atoms. Positive results were obtained in 8 cells out of 23 (see Table VI) (excepting cells that shorted early and hydrogen controls). There were indications that the oxide layer on the metal particles affected the tritium yield.

The group from the Universidad Autonoma de Madrid,<sup>35</sup> in the process of a long (1000-h) electrolysis of heavy water (+  $\text{Li}_2\text{SO}_4$ ) with titanium electrodes, obtained several indications of tritium production. In

### III

#### Electrolysis at BARC

Experiment						
5	6	7	8	9	10	11
Palladium						
6.37	6.37	6.37	2.75	0.57	0.126	4
60	100	80	80	28	3	1.5
350	470	350	800	100	278	7.5
(pulse)	(pulse)	(pulse)				
366 h	183 h	5.8 days	40 days	190 days	17 days	80 days
2.81	2.77	2.70	2.68	4.6	2.0	2.5
$5.9 \times 10^4$	4.6	---	---	72	65	23
21	1.66	2.5	1.9	15.7	32.5	9.16
$2.1 \times 10^6$	$3 \times 10^3$	$6.3 \times 10^2$	$1.1 \times 10^3$			
$1.1 \times 10^{15}$	$1.56 \times 10^1$	$3.96 \times 10^1$	$5.8 \times 10^{11}$	$10^{12}$	$10^{11}$	$2 \times 10^{10}$
	2	1				
$1.7 \times 10^{14}$	$2.4 \times 10^{11}$	$6.2 \times 10^{10}$	$2.1 \times 10^{11}$	$1.8 \times 10^{12}$	$0.8 \times 10^{12}$	$0.5 \times 10^{10}$

TABLE IV  
Tritium Production During Gas Saturation of Palladium with Deuterium at BARC

	Experiment				
	1	2	3	4	5
Sample material	Palladium	Pd-Ag	Pd-Ag	Pd-Ag	Pd-Ag
Mass (g)	20	0.96	10.9	10.6	0.43
Volume of absorbed D <sub>2</sub> (ml)	1325	34.5	516.4	222	20.2
D/Pd ratio	0.63	0.46	0.45	0.20	0.45
Equilibrium time (h)	16	16	240	40	240
Volume of water used for extraction (ml)	50	6	50	50	5
Tritium activity of water (Bq/ml)	8.1	5.9	8.5	12.5	32.6
Tritium absolute activity (Bq)	411	37	429	718	159
Deuterium ratio on palladium	$32 \times 10^{-11}$	$1.1 \times 10^{-11}$	$0.87 \times 10^{-11}$	$3.4 \times 10^{-11}$	$8.3 \times 10^{-11}$
Total number of tritium atoms in palladium	$2.3 \times 10^{11}$	$2 \times 10^{10}$	$2.4 \times 10^{11}$	$4.1 \times 10^{11}$	$9 \times 10^{10}$
Number of tritium atoms per gram of palladium	$1.2 \times 10^{10}$	$2.10 \times 10^{10}$	$2.2 \times 10^{10}$	$3.8 \times 10^{10}$	$20.8 \times 10^{10}$

TABLE V  
Tritium Production During Gas Saturation of Titanium with Deuterium at BARC

	Experiment		
	1	2	3
Sample mass (g)	0.98	0.206	0.2
Mass of absorbed D <sub>2</sub> (mg)	0.42	0.07	0.29
Activity from count of X-radiation quanta (Bq)	290	1300	$5.5 \times 10^{-6}$
Number of tritium atoms	$1.5 \times 10^{11}$	$6.5 \times 10^{11}$	$3 \times 10^{11}$
T/D ratio	$1.2 \times 10^{-9}$	$3.2 \times 10^{-8}$	$7.1 \times 10^{-5}$

two cases, four- and eightfold increases in electrolyte tritium scintillation counts were obtained within a few hours of the start of electrolysis and fell smoothly over the next 1200 h to the asymptotic limit expected for open cells (about twice the initial concentration). In another case (see Fig. 20), the asymptotic limit was reached after ~500 h, but at 800 h an additional smooth increase in tritium concentration occurred that lasted at least 400 h, roughly linear to 50% beyond the asymptotic limit. Contamination from ambient sources would have had to have been remarkably constant, in just one cell of many, over 20 days to give this result. Conceivably, cations promoting a tritium-to-deuterium separation factor of >2 could have begun to plate out on the electrode.

In addition to these positive results on tritium, Wolf presented negative results that denied previous data that had pointed to significant formation of tritium during palladium electrolysis. Other measurements conducted on >100 electrolytic cells exhibited no

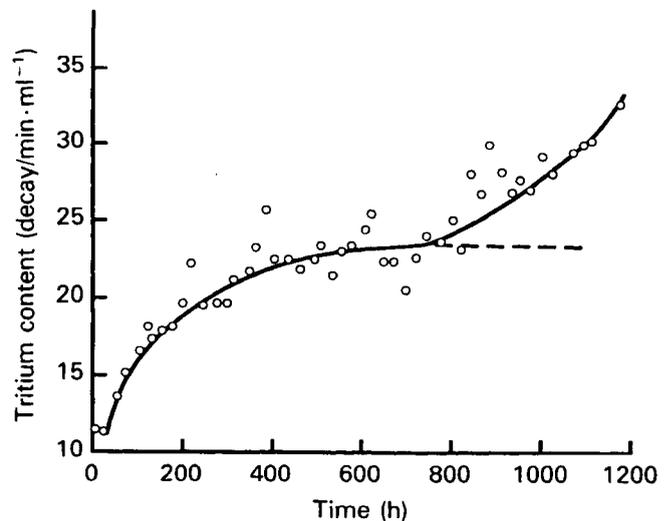


Fig. 20. Tritium concentration of electrolytic cells in Ref. 35.

TABLE VI  
Data on Tritium Content of Claytor et al.'s Pd/Si Device\*

Sample	Total Tritium (nCi)	Run Time (h)	Cell Type	Fill Gas <sup>a</sup> and Pressure	Notes
1	Not analyzed	3	4 palladium layers, 12 g	D1, 7.5 atm	Sample shorted out
2	170 $\mu$ Ci	96	4 palladium layers, 12 g	D1, 7.5 atm	5% hydrogen added to cell on April 26
3	Not analyzed	20	4 palladium layers, 12 g	H1, 7.5 atm	Hydrogen control
4	Not analyzed	<1	4 palladium layers, 12 g	D1, 7.5 atm	Leaky seal
5	Not analyzed	<1	4 palladium layers, 12 g	D1, 7.3 atm	Leaky seal
6	No	17	4 palladium layers, 12 g	D1, 7.4 atm	Sample shorted out
7	68	95	4 palladium layers, 12 g	D1, 7.2 atm	Repeat of sample 2
8	<2	142	Palladium mixed layers, 11.6 g	D2, 13.6 atm	Palladium and silicon powders mixed
9	<2	63	3 palladium mixed layers, 11 g	D1, 8.8 atm	Same as 8, but outgassed at 110°C
10	320	77	4 palladium layers, 12 g	D2, 17 atm	Repeat of sample 2
11	15	162	4 palladium layers, 12 g	D3, 17 atm	Leaky seal
12	44 $\pm$ 2	62	6 palladium layers, 18 g	D3, 17 atm	Cell shorted after 62 h
13	<2	169	6 palladium layers, 18 g	D3, 20.4 atm	Repeat of 12 but no oxide on palladium
14	10	110	6 palladium layers, 18 g	D3, 20.4 atm	Repeat of 12
15	6	106	6 palladium layers, 18 g	D3, 40.8 atm	Repeat of 12
16	<1	22.2	7 palladium layers, 12 g	D3, 34 atm	Sample shorted out
17	12 $\pm$ 3	112	6 palladium layers, 18 g	D3, 40.8 atm	Repeat of 12 but higher fill pressure
18	<1	86	6 palladium layers, 18 g	D3, 40.8 atm	Repeat of 12 but sulfur surface treatment
19	56	124	8 palladium layers, 15 g	D3, 54.4 atm	Silicon with dow binder and palladium heated to 350°C
20	214	356	11 palladium layers, 19.5 g	D3, 54.4 atm	Silicon with dow binder and palladium heated to 350°C
21	75	85	8 palladium layers, 14 g	D3, 54.4 atm	Silicon with dow binder and palladium heated to 350°C
22	11	49	8 palladium layers, 14 g	H2, 54.4 atm	Silicon with dow binder and palladium heated to 350°C
23	<0	13	13 palladium layers, 18 g	D4, 54.4 atm	Sample shorted. Material treatment same as 19
24	13	522	7 palladium foils, silicon wafers	D4, 54.4 atm	7 10-mil foils plus two powder end caps, 21.6 g total
25	6	112	8 palladium foils, silicon wafers	D4, 54.4 atm	8 10-mil foils plus two powder end caps, 24.2 g total
26	10	190	10 palladium layers, 14.4 g	D4, 54.4 atm	Same as 19, native oxide and PVA binder
27	1.5	65	10 palladium foils, silicon wafers	D4, 54.4 atm	10 10-mil foils plus two powder end caps, 29 g, PVA
28	11	182	11 palladium layers, 15.6 g	D4, 54.4 atm	Same as 20 but native oxide
29	4	66	10 palladium foils, silicon powder	D4, 54.4 atm	26.4 g total palladium, silicon powder with dow
30	20	61	7 palladium layers, 13.4 g	D5, 9.5 atm	Repeat of 19 but shorted after 61 h
31	0	15	10 palladium foils, silicon powder	D5, 43.8 atm	29.6 g total palladium, shorted after 15 h
32	6	198	7 palladium foils, silicon wafers	D5, 13.6 atm	16.19 g total palladium

\*Taken from Ref. 34.

<sup>a</sup>Tritium in deuterium bottles ( $\mu$ Ci/m<sup>3</sup>): D1 110  
D2 28  
D3 20  
D4 68  
D5 17

tritium production. More than 100 samples of stock palladium gave two indications of tritium that could definitely not be considered due to CNF. According to Wolf, the tritium excesses observed in his earlier work were most likely due to contamination in the electrode metal and perhaps in the electrolyte.

In the discussion of this paper and in some other subsequent communications, Wolf's point of view was criticized. Cedzynska [National Cold Fusion Institute (NCFI)] informed the conference<sup>36</sup> of work conducted especially to check the possibility of impurities in palladium as a source of excess tritium. In the NCFI tritium assay method, catalytic oxidation and distillation steps were included in a closed analysis system. This eliminated traces of metals that were believed to be responsible for high tritium counts in some samples that did not contain tritium. Their check of 45 palladium samples with different metallurgical histories and of variable size, produced by three different companies, showed no signs of tritium impurities even with the open analysis system. Within the limits of experimental error ( $\pm 1 \text{ decay} \cdot \text{min}^{-1} \cdot \text{ml}^{-1}$ ), those samples gave a tritium count at the background level ( $26 \text{ decay} \cdot \text{min}^{-1} \cdot \text{ml}^{-1}$ ). A further 90 samples from two manufacturers (including Wolf's source) all gave tritium assays from the closed system at the background of  $27 \pm 1 \text{ decay} \cdot \text{min}^{-1} \cdot \text{ml}^{-1}$ . The authors point out that the use of open electrolyzers could lead to unreliable results provided no special precautions are taken.

### CORRELATION EXPERIMENTS

The experiments considered in the previous sections, in which metal lattices are deuterided in various ways and specific nuclear fusion products (neutrons, protons, gamma quanta, and tritium) are registered, could be classified as traditional. Along with these, the results of first experiments of a new kind were presented, the so-called "correlation" experiments, where simultaneous detection was made of both nuclear reaction products and possible signals from "accompanying" phenomena.<sup>1</sup>

A series of experiments conducted by LPI-LMI-LSU capitalized on the experience of the Golubnichyi group at LMI in studies on radiation acoustics and mechanoemission.<sup>23,24</sup> They searched for time correlations between pulses of nuclear (proton), electromagnetic, and acoustic emission in electrolytic saturation of palladium foils with deuterium, where the palladium was part of the cell wall. The following transducers and instrumentation channels were positioned close to the samples: (a) nuclear: CsI scintillator viewed by a photomultiplier; (b) acoustic: piezoceramic chip soldered to the palladium electrode; and (c) electromagnetic: toroidal coil with an amplifier having an amplification factor of  $\sim 10^4$  and a passband of  $\sim 1 \text{ MHz}$ . Average backgrounds in the channels were, respectively,  $\sim 10^{-3}$ , 400, and  $\sim 0.03/\text{s}$ . The starting pulse

was produced by the CsI scintillator. Acoustic pulses had a  $10\text{-}\mu\text{s}$  delay that made it possible to register an acoustic signal that preceded a nuclear pulse. Triple correlations were sought in a time interval of  $10 \mu\text{s}$ . During 15 h of reference measurements with electrolysis of  $\text{H}_2\text{O}$ , not a single triple coincidence was registered.

During three experiments with electrolysis of  $\text{D}_2\text{O}$  with a total duration of 11.5 h, two events with triple coincidences were detected.<sup>23</sup> Their oscillograms are presented schematically in Fig. 21. In both cases, the acoustic pulse was initiated 2 to  $3 \mu\text{s}$  earlier than the proton starting pulse, which is expected from the viewpoint of the "accelerating mechanism" theory.<sup>1</sup> The expected number of chance coincidences during the time of measurements was  $\sim 10^{-7}$ . One more correlation of a proton burst and acoustic emission was registered during the thermal desorption of deuterium while heating the deuterided palladium foil.

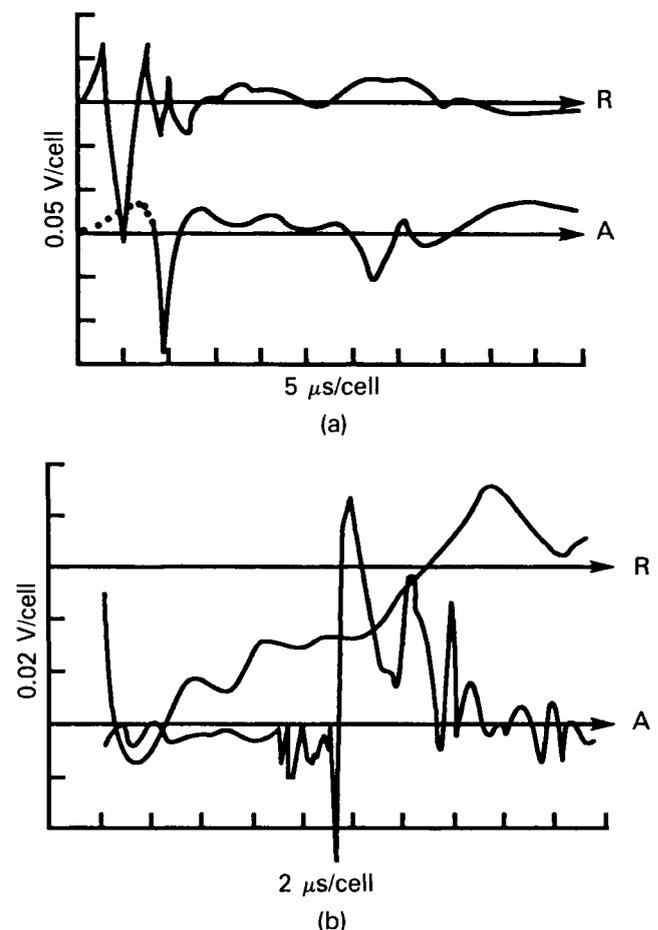


Fig. 21. Oscillograms of events demonstrating the time correlations of the proton: acoustic (A) and radio (R) emissions from a palladium target. The oscilloscope was triggered by the CsI scintillation detector signals.

Unfortunately, this experiment has some disadvantages:

1. The number of events detected was very small.
2. There is a possibility of triggering the detector with X-ray quanta accompanying the cracking of palladium hydride, although the control experiment with H<sub>2</sub>O would exclude this factor for good statistics.
3. A contribution is possible from correlated background, induced by the interaction of cosmic-ray particles, which can produce fast nucleons and which might simultaneously cause cracking in stressed material of a hydride.

To eliminate these disadvantages, the LPI-LMI-LSU group performed a further experiment<sup>24</sup> in a well-screened, low-background laboratory at the Baksan underground neutrino observatory of the Nuclear Research Institute of the Academy of Sciences of the USSR. Use was made of a chamber constructed for studying double beta decay at a depth of 1000 m of water equivalent, with utilization of low-background materials. The chamber background was considerably reduced as compared with typical laboratory conditions at sea level, for instance, as much as  $\sim 10^4$  times for muons and by  $\sim 10^3$  times for gamma quanta (of 0.2- to 3.0-MeV energy). Unfortunately, these fine conditions were not fully used since the neutron detector contained radioactive impurities. As a result, they had  $N_\gamma \sim N_{\gamma \text{ lab}}/200$  and  $N_n \sim N_{n \text{ lab}}/30$ , which gave  $\sim 4 \times 10^{-3}$  slow neutrons per second in the detector ( $10^3$ He tubes in paraffin, 10% efficient).

In auxiliary experiments, the central block of paraffin moderator was replaced by a fast neutron detector and a <sup>252</sup>Cf source to obtain the neutron moderation time distribution for the experimental geometry, presented in Fig. 14a. Typical moderation times were several tens of microseconds. In the main series of 4 h of measurements, coincidences between slow neutrons and acoustic pulses were detected; to stimulate the effect, they used current cycling and sample cryocooling. With a 100- $\mu$ s time gate, 42 coincidence events were detected from neutrons and acoustics (only during the thermal cycling), with  $\sim 5$  expected random coincidences. The good agreement between the shape and timing of the neutron moderation curve (see Fig. 14a) and the distribution of relative arrival times between neutrons and acoustics (see Fig. 14b) confirms the origin of the signals. The authors stated that control experiments excluded artifacts (see Figs. 14c and 14d).

Proton emission and electromagnetic radiation correlation was also observed in the experiment performed by Li et al.<sup>33</sup> (Tsinghua University) with gas loading of palladium samples.

Taniguchi and Yamamoto<sup>37</sup> (University of Osaka) found high-frequency current signals at the electrolytic cell anode arising at the beginning of electrolysis. How-

ever, they were not able to establish to what extent the signals correlated with proton emission events.

Signals of acoustic emission in experiments with gas charging of palladium and titanium were detected by the group from LANL and BYU, who used them to detect sample cracking, but these signals were reported to not be in coincidence with the neutron spikes described earlier.<sup>3,4</sup>

## EXPERIMENTAL TECHNIQUES

An important aspect of work on CNF is the improvement of detection instruments and the techniques for conducting experiments. Much of the conference material was concerned with this field.

Conceptually, the neutron detection techniques underwent no substantial changes. To detect fast neutrons, solid and liquid scintillators are used, with pulse-shape discrimination systems for  $\gamma/n$  separation. Slow neutrons are detected with <sup>3</sup>He and BF<sub>3</sub> proportional counters. At the same time, the efficiency (up to  $\sim 45\%$ ) and the noise immunity of the detectors have improved considerably. In some facilities, the operation of separate detector segments is checked to exclude interference and faulty operation. A reliable technique is neutron detection both before and after moderation, first used for CNF by Jones et al. and then employed in experiments at LPI-LMI and some others.

Unlike experiments on CNF conducted during the initial period, much attention is now being paid to suppressing the background. In a number of measurements, low-background underground laboratories were used.

Three groups conducted work in the Gran Sasso neutrino laboratory; the group from the LPI-LMI-INR utilized a low-background chamber of the Baksan underground neutrino observatory; the group from the China Institute of Atomic Energy performed measurements in the Mentou laboratory at a depth of 580 m; and Jones, Menlove, and Wolf performed some key experiments in a lead mine in Colorado. Menlove and Claytor are now routinely working in a tunnel at LANL. This has made it possible to reduce the background contributed by cosmic rays by three to six orders of magnitude. Under such conditions, the greatest background is contributed by radioactive impurities in materials of the instruments and in surrounding rocks. In the Baksan low-background chamber, the latter background source is also substantially suppressed. Special low-background materials are therefore beginning to be used for constructing detectors for CNF. Particularly suitable for underground use is the type of fast neutron scintillation detector used by Wolf and others, which has a low intrinsic background.

An extremely interesting prospect for experiments on CNF is the use of the underground Cherenkov detector at Kamioka proposed in the report by Totsuka<sup>38</sup>

(University of Tokyo). It was proposed to place an active CNF sample into a nickel cylinder to detect gamma rays from the neutron capture reaction  ${}^A\text{Ni}(n, \gamma){}^{A+1}\text{Ni}$ . The isotopes  ${}^{58,60,62}\text{Ni}$ , making up 68, 26, and 3.7% of natural nickel, respectively, will produce gamma rays with energies of 9.0, 7.8, and 6.8 MeV, respectively, which will be detected with  $\sim 10\%$  efficiency. Taking into consideration the very low background rate, it is possible to obtain a neutron sensitivity (at 90% confidence level) of  $4 \times 10^{-5}$  n/s ( $1 \times 10^{-5}$  n/s), at a gamma threshold energy of 7 MeV (8 MeV), which exceeds the existing level by at least three orders of magnitude. It is also possible to detect gamma quanta from the reaction  $p + D \rightarrow {}^3\text{He} + \gamma$  under practically backgroundless conditions. At the time of writing, experiments have been started at Kamioka, in collaboration with Jones, Menlove, and Wolf.

Frequently, charged particles are detected using surface-barrier detectors, which make it possible not only to detect the particles and find their energy but, with the use of  $\Delta E/E$  telescopes, to identify the particles in real time.

To detect tritium, various techniques are used, including direct counting of beta activity by liquid or solid scintillators, active detection of X rays, radiography, etc. Utilization of different techniques makes it possible to increase data reliability, although assay preparation was itself a hot topic at the meeting.

Correlation measurements were mentioned in the previous section. These are of interest not only from the viewpoint of explaining the nature of CNF, but, should the existence of correlations be confirmed by subsequent studies, this technique can become a convenient and effective way of suppressing background and discriminating weak signals.

In earlier work<sup>1</sup> at LPI-LMI, it was hypothesized that CNF could be triggered by means of various external effects: ultrasonics, thermo-, cryo-, and current cycling, mechanical strains, etc. At this time, some of these means are widely used and evidently lead to CNF intensification. Thus, thermal cycling, used for the first time by the Frascati group, is now widely used in experiments on metal charging with deuterium from the gas phase. In papers by the groups from Osaka University,<sup>19</sup> Centro Atomico Bariloche,<sup>17</sup> LPI-LMI (Refs. 23 and 24), University La Sapienza,<sup>15</sup> and others, there was information on the triggering effect of pulsating or stepwise, time-variable current on CNF during electrolysis.

A curious observation was made by Srinivasan (BARC), who claimed tritium formation was stimulated by high-frequency heating of deuterided titanium samples.

Yamaguchi and Nishioka<sup>39</sup> (NTT Basic Research, Japan) reported a new technique for stimulating CNF processes. A 1-mm-thick plate of palladium deuteride was coated on one side with a 100-nm film of gold, preventing deuterium atom escape, and on the other

side with a 10-nm-thick MnO film having a deuterium diffusion coefficient smaller than that of palladium. This layer served as a surface barrier for controlling the rate of deuterium atom escape from the metal. Three such samples were placed in vacuum. Three hours later, the following simultaneous phenomena were found: neutron emission of  $\sim 10^6$  n (analog indicator) continuing for 2 to 3 s, "explosive" emanation of gas, surface temperature rise to  $\sim 700^\circ\text{C}$ , and biaxial deformation of the samples due to uniform expansion on the side coated with the MnO film. At subsequent pumping-outs, the same samples gave two more neutron bursts about as powerful. The next 20 pumping-outs gave no new signals. As the authors underline, their procedure leads to creation, in the vicinity of the surface coated with a MnO film, of a thin palladium layer ( $< 40 \mu\text{m}$ ) with a higher deuterium concentration. Several other papers reported neutron emission coinciding with desorption of deuterium from previously loaded lattices.

Along with traditional sample saturation methods, there was information<sup>33</sup> on successful use of a plasma focus facility at BARC, of an electrolyzer with solid electrolyte at the University of Rochester,<sup>40</sup> and of a molten salt electrolyte operating at  $400^\circ\text{C}$  at the University of Hawaii.<sup>41</sup>

A search for materials other than palladium and titanium to be used as deuterium "accumulators" is going on. Often these are alloys of titanium and palladium, but there were also reports of experiments with amorphous  $\text{Fe}_{90}\text{Zr}_{10}$  (Ref. 27) and high-temperature superconductors  $\text{Y}_1\text{Ba}_2\text{Cu}_3\text{O}_{7-x}$  (Ref. 16), first suggested by Rabinowitz.

Reports presented at the conference contained many interesting "technology" details connected with preparation of samples and choice of conditions for electrolysis and gas charging, as well as with results of structural analyses (by electron microscopy, neutron diffractometry, and X-ray diffraction) and studies on cracking and deformation of samples in the process of hydrogenation. In particular, the groups from LANL and BYU have achieved much improved reproducibility with gas charging of titanium by careful degreasing of samples using methylene chloride, methanol, and water. The Frascati group points to the fact that no positive results were obtained if palladium and titanium electrodes had not been degassed initially or if electrodes were made of superpure titanium.

## CNF AND GEOLOGY

An intriguing aspect of the CNF problem was discussed at a special session on geochemical and geophysical studies. Some of the reports contained assumptions on the role that could be played by CNF processes in the life of our planet, particularly in the abundance of certain isotopes and even, possibly, in its energy balance.

The report by Palmer<sup>42</sup> (BYU) contained the following arguments that could give evidence of CNF processes going on in the earth's interior:

1. The concentration of  $^3\text{He}$  in the atmosphere is too high unless one assumes the existence of a constantly acting source of this element.
2. In volcanic gases, liquids, and lavas, an unexpectedly high  $^3\text{He}/^4\text{He}$  ratio is observed.
3. Tritium, an unstable element with a half-life of 12.4 yr, is present both in volcanic gases and in the water of hot springs.
4. Volcanic heat, associated with subduction of cold, water-bearing sedimentary rocks, proves to be too high if it is to be explained only by frictional heat generated by gravitational potential energy and by the heat of surrounding rocks.
5. While ordinary radioactivity, due to uranium, thorium, and potassium, is not associated with hot points of the earth but exists in cold continents, nuclear fusion products, on the contrary, are detected in hot points.
6. Recent estimates of the earth's radiogenic heat source point to insufficient uranium, thorium, and potassium to explain the heat balance of our planet and the high temperature of its core.

Britton<sup>43</sup> (Riess Foundation) reported the analysis of samples taken during deep drilling in the shear zone of the state of Massachusetts. It was found that the concentration of tritium and  $^3\text{He}$  increases approximately linearly with depth, pointing to the presence of a single source of these elements or a constantly occurring process involving both these isotopes.

An anomalously high tritium content in the lavas of the Mount St. Helens volcano was found by a group from LANL (Ref. 44). The studies have shown that a considerable amount of atmospheric moisture is cycling through the cracking lava. Tritium accumulation is possible both due to natural processes (CNF) and as a result of contamination connected with nuclear weapon tests.

In the report by McMurtry<sup>45</sup> (University of Hawaii), there were data on a large anomalous increase in tritium content in the atmosphere detected by the Mauna Loa tritium monitoring station in Hawaii in February and March 1978. The data analysis points to a possible correlation with the concurrent eruption of the Mauna Ulu volcano situated 40 km from the station and the occurrence of suitable winds at the time, whereas a relation with the test of a Soviet hydrogen bomb 5 months before the observations is scarcely probable. These and other similar data suggest the necessity of more thorough investigation into the possible role of CNF processes as a source of some light isotopes and, maybe, heat in the earth.

## CNF MODELS

At the conference, no unique, universally recognized point of view was formulated on the mechanism of CNF. It is not possible in this brief review to consider in detail the various theoretical models and physical concepts contained in a score of reports presented in the theoretical sessions. Therefore, we confine ourselves only to brief remarks on some directions that are being followed in the search for an answer to the nature of this phenomenon.

A long-standing idea<sup>46</sup> has been that of an "accelerating" or "fracto-acceleration mechanism" (FAM). In FAM, fusion is not actually "cold" (as in muon catalysis), but "microhot." The energy required to overcome the Coulomb barrier is imparted to the ions by acceleration in cracks arising in the process of metal loading with hydrogen isotopes.<sup>1</sup> The strongest evidence in favor of FAM are the results of correlation experiments. It was also shown in the reports by the LPI-LMI group<sup>23,24</sup> that many other predictions formulated earlier on the basis of FAM have some experimental evidence (surface-volumetric nature, stochasticity, quasi-periodicity, nonequilibrium of the metal/deuterium system, and possibility of external effects, for example, increase of electrical resistance in the "activity" period). At the same time, there are a number of problems connected with the necessity for rather strong fields in cracks and with the characteristic times of different concurrent processes.<sup>46</sup> Additionally, if the prevalence of the tritium channel over the neutron channel is eventually demonstrated, FAM would need to be modified to account for the inequality. Some possibilities in this respect were discussed by Kim<sup>47</sup> (Purdue University) in connection with the Efimov effect (an infinite number of levels in a three-body system in the presence of a zero-energy level in a two-particle system). The difference between  $\text{D}(\text{D},p)\text{T}$  and  $\text{D}(\text{D},n)^3\text{He}$  could be a consequence of the interaction in the final state.

In connection with the problem of "strong fields," the report by Preparata<sup>48</sup> (NCFI) contained the idea of a possible unification of FAM and an approach considering coherent electrodynamic effects in a condensed medium.

Danos (National Institute of Standards and Technology) and V. Belyaev (JINR) pointed out the possibility of enhancing the probability of deuterium nuclear fusion by virtual interactions in the Coulomb field of lattice ions.<sup>49</sup> This effect might also explain the prevalence of the tritium channel.

In some papers, the authors turned to exotic particles for an explanation of CNF. Thus, in reports by Rafelski<sup>50</sup> (University of Arizona) and Shaw<sup>51</sup> (University of California-Irvine), by analogy with muon catalysis, a scenario is suggested where CNF arises due to catalysis initiated by heavy particles (integrally charged hadrons or fractionally charged, free, stable

antiquarks). A supposition on the emission of new light particles in CNF processes was introduced in the report by Matsumoto<sup>52</sup> (Hokkaido University). Similar models possess very interesting properties, but to explain one strange phenomenon, they involve other, still more hypothetical, effects.

A considerable number of reports were dedicated to specific features in the process of nuclear fusion due to collective effects arising in the crystal lattice.<sup>53-58</sup>

Vysotskii and Kuz'min discussed<sup>21</sup> conditions under which deuterons trapped in microdefects in crystals could participate in "thresholdless fusion" brought about by strong overlapping of their wave functions. Cerafolini<sup>59</sup> (EniChem, Italy) hypothesized the production of metastable exotic "binuclear atoms," ( $D^+ + D^+$ ) $2e^-$ , preceding the process of fusion.

Other work obtained limits on the nuclear fusion cross section at very small energies. Zakowicz and Rafelski<sup>60</sup> (University of Arizona) have shown that the data currently available on cross sections of D-D and *p-t* reactions at low energies substantially limit the effect of possible nuclear resonances and exclude an explanation of CNF on that basis. Another limitation on the D-D cross section was obtained by Gajda<sup>61</sup> (University of Arizona) from estimating the excess heat of the planet Jupiter. Conclusions based on Jovian energy balance are approximately nine orders of magnitude less sensitive than are the laboratory experiments at providing information on CNF. Finally, Vaselli<sup>62</sup> (CNR, Italy) confirmed results obtained earlier concerning the insufficiency of screening effects in palladium crystals for giving agreement with CNF results.

Rabinowitz<sup>63</sup> (EPRI) suggested an important role for heavy ions of the projectile in explaining anomalously high fusion rates using ( $D_2O$ )<sub>n</sub> cluster ions and deuterated targets.<sup>64</sup>

Summarizing the conference in his final speech,<sup>65</sup> Worledge underlined the following items:

1. The phenomena observed are not "normal" D-D fusion.
2. Theory is not yet sufficiently oriented by experiment.
3. The quality of many experiments had improved considerably.
4. There are many very different experiments, but the results seem to be broadly similar.
5. The research field under development has every right to its existence and deserves support.

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