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IN QUEST OF A TRIGGER MECHANISM FOR NEUTRON EMISSIONS FROM DEUTERIUM/SOLID SYSTEMS

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INTRODUCTION

Our search for cold nuclear fusion in condensed matter began with electrolytic and deuterium-gas loading experiments at BYU in 1986. [1,2] In that year, we obtained evidence for neutron emissions, and we pursued our program of neutron detector development, which was hampered by low funding levels.[3] By December 1988, we had in hand a spectrometer to measure neutron energies [4]. We began applying the neutron spectrometer to search for neutron emissions during deuteron infusion into various metals and salts. In a few months of running, including light-hydrogen control studies and detector calibrations, we observed what we discerned (and still maintain [5]) to be significant neutron emission from partially-deuterided materials in non-static conditions and published our results (ref. 1). The rates observed were far too tiny to account for "excess heat" emissions in electrolytic cells reported about the same time [6] and unfortunately connected erroneously with our work. It is true that Van Siclen and Jones in an original paper on "piezonuclear fusion" written in 1985 [7] had discussed the possibility of "excess heat" (our 1985 terminology) in Jupiter due to d-d or p-d fusion in its **metallic** core, but this occurs on a far grander scale than achievable in the laboratory. The hypothesis of the occurrence of natural fusion [1,2,7] inside Jupiter or other planets remains an open and intriguing question (see papers by E. Paul Palmer and others in this Proceedings).

In normal scientific fashion, we checked the results of ref. 1 by carrying out similar experiments with colleagues in Italy [8] and Los Alamos National Laboratory [9], with both experiments reporting anomalous neutron emissions from deuterium/metal systems under non-equilibrium conditions. The Los Alamos experiments showed a surprising aspect of these anomalous emissions, that is, bursts of hundreds of neutrons were detected in time windows of 128 μsec. (Our neutron spectrometer was too low in efficiency to delineate such bursts, but the detector developed by H. Menlove et al. [10] detected bursts clearly.) Random or uncorrelated neutron emissions were also reported at the 10σ level. [9]

We have since repeated our electrolysis experiments in different detectors with higher sensitivity and observed neutron yields up to about 28 times the background level and about 90 standard deviations significance (discussed below; see also Ref. 11). In addition, neutron bursts were detected at BYU in a system that incorporated both the spectrometer and a flux monitor.[11] The flux monitor was similar to the spectrometer but used mineral oil instead of liquid scintillator. Capture times were recorded for neutrons detected following a proton-recoil event above 1 MeV in the spectrometer. The result implies that neutrons having $E_n > 1$ MeV participated in the bursts. A rigorous statistical analysis was included in this study [11]. Thus, while our original results were significant at the $> 4\ \sigma$ level [1,5] the question is no longer one of statistics.

In the experiments, we have been able to reproduce the effect in the sense that neutron emissions appear to be rather similar in divergent detectors (e.g., neutron energies, emission rates and length of neutron-emission episodes) and only with partially-deuterided materials. However, we have been unable to trigger the effect at will. We have assumed that this problem reflected the lack of a cohesive model for the phenomenon and its novelty. Nevertheless, we began a search for triggering mechanisms, in order to:

- rule out the possibility of strange systematic effects in (diverse) detectors,
- accelerate the study of the phenomenon, particularly to benefit theoretical efforts,
- allow for scaling of the effect, and
- permit definitive tests elsewhere of the observations.

This paper traces these searches. Without a cohesive model to guide experiments, we used the hypothesis that non-equilibrium conditions are essential (as we mapped out in 1986 [1,2]). We found that a combination of rapid temperature changes and mechanical stressing has given the most repeatable neutron emissions to date, but we cannot yet claim an immediate trigger. It is clear that experimental variables such as surface conditions and deuterium-absorption rates are difficult to control and that a clear theoretical picture may be needed to give full reproducibility of the nuclear effects. However, we hope that our results and trials will help other researchers as we endeavor to untangle the puzzle posed by signals evidently representing nuclear particle emissions from partially deuterided materials near room temperature.

SEGMENTED NEUTRON DETECTOR USED UNDERGROUND

In order to survey possible fusion reactions with a sensitive, reliable and still portable instrument, the BYU team secured from JOMAR Corporation (Los Alamos, NM) a detector based on helium-3 tubes embedded in a polyethylene moderator. The compact, high-efficiency detector was developed by Howard Menlove (Fellow, Los Alamos National Laboratory) and colleagues as part of the nuclear safeguards program. Detailed descriptions of the detectors can be found in refs. 9, 10. The detector is very sensitive to thermal neutrons, which are captured by helium-3 nuclei, and essentially transparent to gamma rays. The detector was calibrated to have 34% efficiency using a weak californium-252 source (average neutron energy = 2.3 MeV). The efficiency was verified in preliminary experiments done at Kamioka, Japan, using a depleted uranium source.

Our detector configuration is displayed in Fig. 1. There are 16 helium-3 tubes arranged into 4 segments with separate signal outputs. Most of the time we used optical read-outs for the four segments (avoiding penetration into the sealed electronics; see below) in addition to a readout from the "JSR-11" box for the integrated system. In the Kamiokande laboratory, we employed two JSR-11 boxes in the configuration shown in Fig. 1, that is, we used one box to monitor the inner ring of 8 tubes and the other to monitor the total system. Thus, automatic read-outs were available from two detectors, effectively, and we checked the ratio of counts from two separate rings in order to eliminate spurious signals. The inner ring-to-outer ring ratio of counts (I/O) was 1.3 in the deep-underground background. (The ratio is accounted for since segment-four tubes, in the quieter outer ring, were hand-selected for low wall-radioactivity). With a depleted uranium source inside the 8.9 cm cavity in the inner ring, the I/O ratio was 2.0.

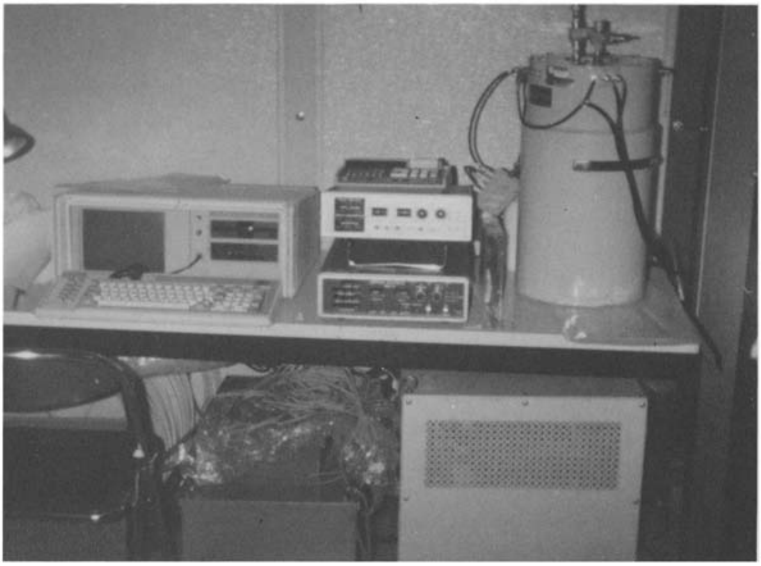


Figure 1a. Photograph of detector (right) holding two sample cylinders, also two JSR-11 analyzers (see text) and portable PC for data acquisition. (Set-up in Kamioka, Japan).

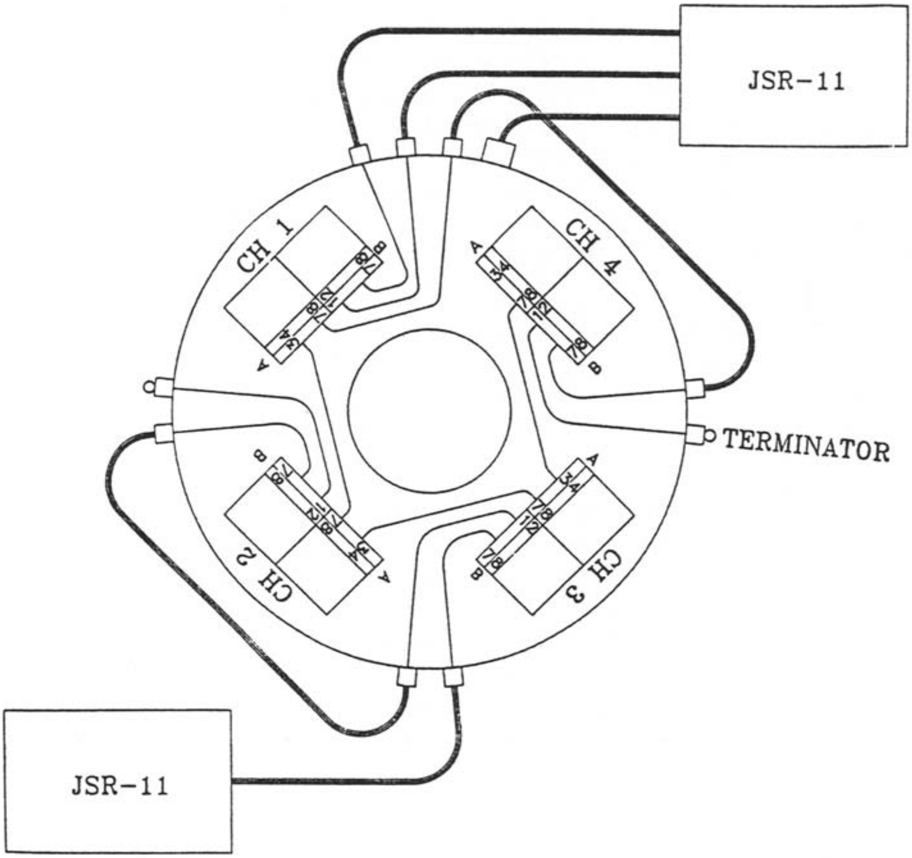


FIGURE 1b.
CABLE HOOK−UP FOR TWO CHANNELS
CHANNELS 1 & 4 = OUTSIDE RING
CHANNELS 2 & 3 = INSIDE RING
NEUTRON DETECTOR WITH 16 HELIUM-3
FILLED PROPORTIONAL COUNTERS,
IN TWO SEPARATE RINGS

Each JSR-11 box provides for two types of neutron-counting [10]:

1) "totals" or counts of single neutrons. To reduce deadtime losses, neutron counts are stored in a derandomizing buffer before they enter the shift-register electronics. Of course, neutron moderation and the use of 16 tubes helps to avoid pile-up of signals from any neutron bursts.

2) "reals" or effective counts of time-correlated neutrons. Every signal triggers the time-correlation registers that check whether there are any other neutrons within the time gate, selected to be 128 μs, which corresponds to about three times the mean neutron die-away time of the detector. The time-correlated count R is related to the number of neutrons (N) that are detected by $R = N(N-1)/2$. If the duration of a burst event plus the thermalization time lasts more than 128 μs, the multiplicity value N will be underestimated.

We have developed new circuitry at BYU to provide a time-tag for each signal from each detector quadrant thus permitting both neutron singles and neutron "burst" counting. This microprocessor-based circuitry fits as a board into the same PC computer used for data acquisition with the JSR-11 box. Our time-tagging circuitry has been tested and will be implemented in future runs.

Radioactive decay from counter-tube walls is a limiting factor in deep underground locations, so our detector was made using stainless steel tubes rather than the usual aluminum walls. This reduced the intrinsic background by about a factor of five, to 70-75 counts per hour in deep mines for all sixteen tubes combined. The proportional-counter tubes are inserted directly into an aluminum cavity that is sealed to prevent rf noise pickup. Charge-sensitive preamplifier/discriminators [10] are placed at the base of the ^{3}He counters to eliminate analog-signal transmission lines prone to noise pickup. We checked the effectiveness of this isolation when we ran the detector near a CO_2 laser, a well-known rf noise generator, and saw no noise pick-up by the detector whatsoever. We inserted abundant desiccant to keep moisture out of the high-voltage area to preclude a noise source.

UNDERGROUND LOCATIONS, BACKGROUNDS, SYSTEMATICS

A frequently-mentioned concern about our observation of low-level neutron emissions is that these could be caused by (fluctuations in) cosmic-ray backgrounds. For example, in the same issue as our original paper in **Nature** [1], John Carpenter cautions that:

> "... in detectors that disperse the spectrum, the evaporation peak in the energy distribution due to cosmic-ray-induced background is at nearly the same energy as the expected from deuteron-deuteron fusion, 2.45 MeV. These observations, coupled with the (admittedly weak ± 10%) temporal (hourly, daily) variation of the cosmic-ray-induced neutron

> fluxes require that this background be carefully accounted for. ... Obvious means for suppressing these backgrounds are ... going underground – 350 g cm-2 (two or three meters of earth or concrete on all sides) should reduce the cosmic-ray neutrons by a factor of about 10." [12]

In fact, our data [1] were taken in an underground laboratory at BYU under approximately two meters of earth and 15 cm of concrete. As Dr. Carpenter was an acknowledged referee of our paper, his concerns were addressed in the published version of our paper [1]. In particular, we found a smoothly decreasing background spectrum, using light-water and other controls, with no structure around 2.5 MeV in the background. We provided further comments on statistics and questions of variations in the background in correspondence to **Nature** [5], showing in particular that the original data set showed a significant ($> 4\sigma$) signal.

To further preclude interference from cosmic-ray influences, we have conducted experiments in deep underground locations. During the summer of 1990, we moved the helium-3-type detector into the Blackcloud mine in Leadville, Colorado. The detector was then shielded by an overburden of approximately 600m of rock including lead and zinc ores. Both the singles and correlated-count rates dropped dramatically in this location (Table I). Similarly low background rates were observed when the detector was run in the Kamioka mine in Japan, with about 1000 m of overburden. (Due to time constraints, we are able to include data from the first few days of this experiment, from the BYU helium-3 counter only. Results from the large Kamiokande detector will not be discussed here.) A comparison of rates in various locations is given in Table I. Note that singles rates are the same in the mines in Japan and in Colorado. This supports our calculations that observed singles rates are due almost entirely to decay of radioactive trace elements in the counter-tube walls. Such decay results in a Poisson distribution of counts, consistent with our observations in the deep-mine environments.

Table 1. Comparison of background counting rates
in dual-ring segmented counter

Location	Singles rate	Correlated-count rate in 128 μs window ("reals")
BYU underground lab	400/hr	7/hr
Leadville, CO		
Above ground	23,400/hr	300/hr
600 m underground	75/hr*	1/20 days

Kamioka, Japan		
1000 m underground	75/hr*	(not enough running time yet to see any burst-like events in background)

*For counts accumulated in 60 second bins. Background rate is about 70/hr for 10-second bin collection intervals due to computer dead-time.

Operation of the detector underground provided an opportunity to scrutinize sources of spurious signals in the detectors. These tests complement extensive tests by H. Menlove and colleagues at Los Alamos showing very high immunity of the counter to gamma-rays, temperature changes, microphonics, and electrical noise pickup as well as long-term stability [see 9,10].

When the detector was first run in the humid environment of the Colorado mine, it was not sufficiently protected from penetration of humidity into the high-voltage circuitry. As a result, we observed a dramatic increase in both the singles and the correlated-signals rates. We accumulated data in this condition in order to characterize the moisture-induced noise. We found that the singles rate was dominated by counts in one segment, that is, segment 4 was counting an order of magnitude faster than the other three segments. Thus, segmentation of the counter allowed us to identify the spurious counts. Apparent bursts had the characteristic that counts in singles scalar were much larger than counts in the "reals" or correlated counts register, typically by factors of 5 to 30, consistent with expectations for high-voltage breakdown or electrical noise induced by high humidity. Again, redundancy in the electronics allowed us to identify spurious burst-like signals. The detector was then dried out, loaded with dessicant, and protected from humidity; a humidity indicator was also monitored. The detector quickly returned to low-count behavior with counts balanced as expected in the four segments.

We also accumulated data with a very loud ventilation fan running; the rates were the same without the acoustical noise. The detector was tapped vigorously with tools with no microphonic pickup. An inadvertent dropping of a $\sim$ 5 kg miner's battery on the detector resulted in a spurious "burst" count, but again the singles scaler was several times larger than the "reals" scaler, showing that the "burst" was spurious.

In a year's experience with the detector in various locations, the largest burst-like event with hydrogen-control samples had R=84, implying a neutron-multiplicity of 38 source neutrons. This event was observed while the detector was above ground in Leadville, Colorado, in an intense cosmic-ray field (see Table I) and is attributed to cosmic-ray-induced neutron spallation. Consistent with this explanation, in the deep mine in Leadville in about three weeks of background running, we saw only <u>one</u> burst-like signal, having R=1, that is, two signals appeared in the 128 μs window. (No bursts have yet been seen in Japan in this detector in control runs.) As we shall see, bursts of multiplicity up to 300 source neutrons were seen deep underground using partially-deuterided materials. It is difficult indeed to ascribe such events to cosmic-ray-induced spallation: interesting physics is strongly evidenced.

RESULTS AND DISCUSSION

We have tried various avenues to inducing neutron-emission events. As we noted in **Nature**:

> "... we conclude that non-equilibrium conditions are essential. Electrolysis is one way to produce conditions that are far from equilibrium. It may seem remarkable that one might influence the effective rate of fusion by varying external parameters such as pressure, temperature and electromagnetic fields, but just such effects are seen in another form of cold nuclear fusion, muon-catalyzed fusion." [1]

Guided by these notions, we tried various approaches, summarized in Table II. Several of these approaches deserve further attention; here we discuss salient results to examine their significance.

Neutron Emissions Using Electrolytic Cell in BYU Underground Lab

We repeated measurements much as in Ref. 1 using an electrolytic cell, but using the sensitive helium-3 type counter. Using [(detector efficiency)^2/background rate] as a figure of merit [14], we find that this counter (merit=$(0.34)^2/0.1 = 1$) is ten times more sensitive than the spectrometer described in [1] (merit=$(0.01)^2/0.001 = 0.1$), although the ^{3}He-type counter does not give the neutron energy. Thus, we hoped to have a further check on our published results [1].

The electrolyte was simply 1M $LiSO_4$ in D_2O. Other conditions are listed in Table II, A. Background runs include approximately four weeks of running with an operating matching cell using H_2O instead of D_2O, with Pd outside the D_2O electrolyte with no current; see Fig. 2b.

An unmistakably significant episode of high-count rate occurred on July 20, 1990 as shown in Fig. 2. The rate reached 28 times the background at one point and overall the excess count rate lasted nearly three hours consistent with our earlier observations using the spectrometer [1]. Background runs are shown for comparison; no such effect has been seen in any background runs (Fig. 2b). Furthermore, no significant signal was recorded at any time in a nearby counter of the plastic/glass scintillator hybrid type. We also checked cosmic-ray fluxes on this day which were neither high nor widely fluctuating. In fact, cosmic-ray fluxes were at a broad minimum during this

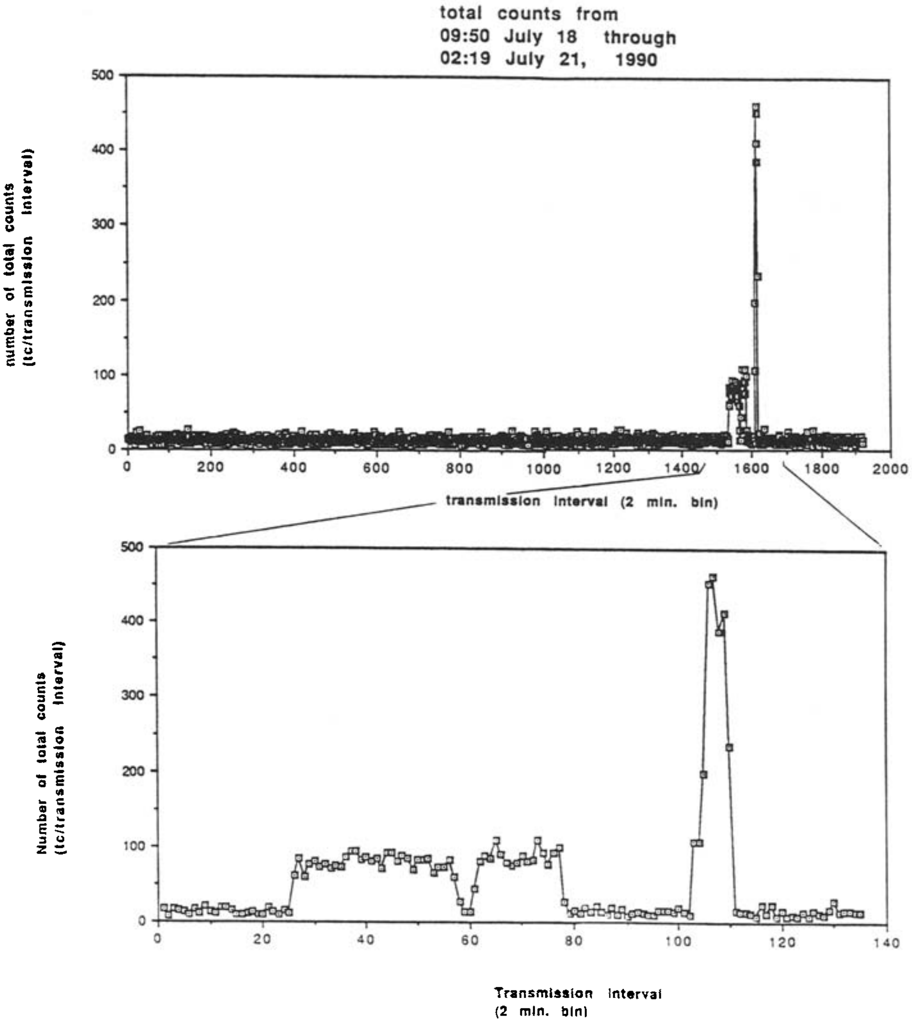
Table II.
Summary of Recent Experiments
in Search of Trigger Mechanisms

Description of Experiment	Comments on Results	References to Related Work
A. Electrolysis 1. Pd cathode 3mm x 3 cm long, 1M $LiSO_4$ in D_2O or H_2O (~ 3 weeks each) Pt anode ramped voltage up slowly to 1.1V (versus reference electrode)	Neutron singles up to 28 x background, approx. 90 σ, 0.08 n^o/sec. average source rate. (see text.) Neutron bursts of multiplicity 35, 125 and 141 neutrons, 3 weeks running, none above 32 with H_2O. BYU underground lab.	1, 6, 8, 9.
B. Electrolyis 2. Pd-wire anode and cathode, x 0.05 cm diam, 3M LiOD or 3M LiOH, ~ 640 mA/cm^2 on cathode at 3.74 volts, closed cell, ion-exchange membrane kept $D_2(H_2)$ and O_2 separate in cell.	Neutron bursts and singles seen; 2 neutron detectors; threshold E_n MeV (proton recoil in plastic scintillator). No anomalous heating or tritium enhancement seen. Rigorous statistical analysis. Published: ref. 11. BYU underground Lab.	1, 6, 8, 9.

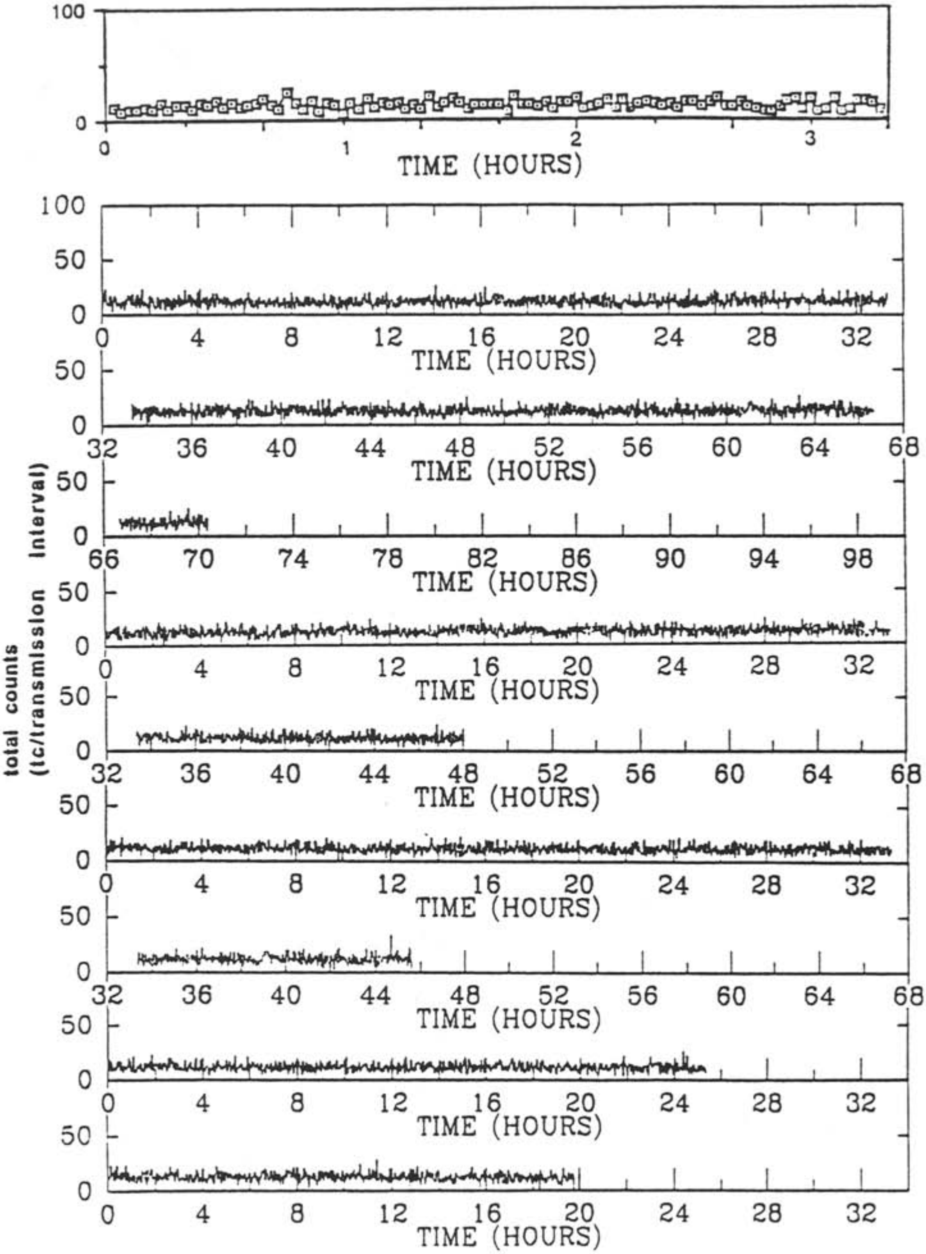
Description of Experiment	Comments on Results	References to Related Work
C. CO_2 Laser on TiD Ti-662 foils, ~ 25 μm thick, heat in vacuum to 470°c, add D_2 at 10 psi (absorbed). CO_2 laser at 1 Hz, $\lambda \approx 10.6 \mu m$, 10J/pulse, focussed caused breakdown in air, burned through TiD foils	No neutron emissions above TiH-chip background, 2 week run. No EMI-pickup by detector from CO_2-laser operation. BYU underground lab.	(none known)
D. Chemical Experiments Pd $(ND_3)_2$ Cl (8gm) + Zn(4g) or FeOOD(40g) + Zn powder (31g), typical masses, (with H-substituted controls)	No significant neutron yields above background. (BYU underground, Colorado mine)	15
E. Gas-loaded Ti chips, LN_2-cycled, also, liquid helium-cooled. High-temp. preparation: Heat to ~ 650°c under vacuum, add D_2 (H_2) gas to form $TiD_{0.2}$, approx. Low-temp. preparation: see steps by M. Paciotti (14)	Neutron bursts seen, see text, ref. 9	9, 14, 16, 17

Description of Experiment	Comments on Results	References to Related Work
F. Pd-foil + D_2 gas, LN_2 cycle 25 μm Pd foil, annealed at 700°c, D_2 (75%) + H_2 (25%) at 12 atm, cool.	Possible charged-particle production in episodes, up to 260 particles/hr; see Ref. 20.	17, 24
G. Pd in D_2-plasma (discharge) Pd foil or wire in ~1/atm D_2, ~ 20KV discharge, then search for neutrons	Bursts of 42 and 280 source neutrons seen in ~ 3 weeks of running. BYU underground lab. (In collaboration with U. of Utah/NCFI scientist John Petersen)	21
H. Cement prepared with D_2O (H_2O), then LN_2 cycled	No significant effects seen. BYU underground lab.	(None known)
I. Barium titanate (also KDP and Rochelle Salt) + D_2 alternating voltages up to 1000 V/cm, temp. 170K → 300K	Experiments just underway BYU underground lab	(None known)

Description of Experiment	Comments on Results	References to Related Work
J. Diamond anvil cell TiD foil, gas-loaded, shattered, placed in D_2O in Ti foil gasket, pressure to ~ 45 Kbar as measured by laser-fluorescence on ruby fragments.	Only one test in Colorado mine: no significant neutron yields.	7,13
K. TiD chips, warm-and-stress; cool in LN_2, remove with pliers, squeeze in detector, also High-T_c superconductor. $Y_1Ba_2Cu_3O_{7-x}$ heated to ~ 300°c, D_2 (H_2) added (~ 0.6 moles gas/285 g superconductor). Cool in LN_2, remove with pliers, shatter in detector.	Both random neutron emissions and bursts seen deep underground, see text.	1, 18, 19 (special thanks to F. Celani for suggesting superconductor material)



2a. Example of high-count rate episode lasting three hours, with expanded time scale in bottom plot. Data were taken with electrolytic cell described in text, using the 16-tube helium-3 type of counter for neutron detection.



2b. Background data to compare with Fig. 2a, showing long-term stability of detector and background in BYU underground laboratory. Data include control runs with matching electrolytic cell loaded with H2O replacing D2O and D2O cells with no current (cathode out of electrolyte).

period corresponding to solar cycles. [25] The statistical significance of the peak above background is estimated at 90 standard deviations; clearly this is beyond statistical fluctuation. The average rate above background is approximately 0.08 source neutrons/second, consistent with the average source rate of 0.06 n/sec reported in [1], but the significance is greater largely because of the higher sensitivity of the counter. While a single episode of this sort is not compelling evidence for nuclear processes, significant neutron emissions were also seen in deep-mine locations, as discussed below, in deuterided samples. Other similar episodes are discussed in Refs. 1 and 9.

There were also a few significant neutron bursts detected in the counter during the same three-week run with the D_2O electrolytic cell. Burst multiplicities as recorded in the reals (totals) register were: 135 (148), 121 (129) and 35 (29), showing good agreement between the two registers. The largest burst detected in three weeks of background running was 32 neutrons, consistent with results of extensive H_2-control runs at Los Alamos [9].

Neutron Burst Results

We obtained evidence for neutron-burst emissions in the Leadville, Colorado experiments, both above and under ground. As mentioned above, we do see small neutron bursts above ground which we have ascertained to be due to cosmic-ray effects. [9] It is important to note, however, that the maximum multiplicity observed with Ti-hydride controls has been 38 neutrons, observed above ground in Leadville. Much larger bursts (100 - 900 source neutrons in 128 μs) have been seen and only with partially-deuterided samples. [9] Nevertheless, it is important to establish whether bursts are seen deep underground to rule out any possible confusion from cosmic rays. In addition, if the rate of large-burst production is greater at high altitudes, this might imply some sort of triggering mechanism by cosmic rays, even perhaps the presence of a catalyzing particle [22].

Underground, we saw one burst of just two signals coincident in 128 μs [R=1] in about three weeks of observation with controls; by contrast, in about the same running period with deuterium-loaded samples, we saw five bursts which satisfied our redundant-electronics checks. Two of these events were large: 71 and 300 source neutrons. The multiplicity= 71 burst was obtained with 35 g Ti 662 (6% Al-, 6% V, 2% Sn) alloy which had been heated to 650°C under vacuum, then pressurized to 2 atm D_2 and cooled under pressure to room temperature. The cylinder was warming from liquid nitrogen temperature when the burst occurred, a previously-noted temperature correlation [9] which also implies that the burst was not due to cosmic rays. (Note that H. Menlove has done extensive tests which rule out the possibility that the detector is sensitive to temperature variations such as might be induced by the warming cylinder. [9]) A small burst (R=1) was later seen at room temperature with TiD prepared the same way.

The large burst of about 300 source neutrons (Fig. 3a) occurred while the author was warming and stressing deuterided materials. The procedure was as follows. TiD chips (prepared by D_2 gas-loading) were kept in a small container with liquid nitrogen. Pliers were used to remove the chips and hold them inside the detector cavity while moderate pressures were applied by squeezing the pliers. Many chips shattered under this treatment. All chips fell into a container inside the detector cavity. The author also processed YBaCuO superconductor (heated to 300°C then pressurized with D_2 gas while cooling) by the same procedure of rapid warming and shattering and let the chips fall into the counter. During this procedure, the burst of 300 source neutrons was seen, with good agreement in the redundant electronics registers. The same material-stressing procedure with TiD chips resulted in a small burst (R=1) to be seen in the counter in the Kamioka mine, the only burst seen in five days of foreground and background runs (including warming-and-squeezing of Ti and TiH control chips). The warm-and-stress method was also applied to deuterided-superconductor chips in Kamioka, with apparent neutron singles production discussed in the next section. (F. Celani suggested the use of the YBaCuO superconductor materials. [18])

A fracto-fusion [19] mechanism may be implicated by these results, but two facts obscure the picture. First, processed chips fall into the counter and these may be the source of the signal as opposed to chips being actively fractured. That is, the cracking may not be simultaneous with neutron production [see ref. 9 in this regard]. We will check this by warming and grinding chips inside various detectors and carefully checking for simultaneity of stimulus and signal. Secondly, we observed singles neutron production while repeating the procedure (see next section), not just bursts as might be expected in the micro-hot-fusion model [23].

Above ground in Leadville, at an elevation of about 3300 m, we saw two bursts larger than we have ever seen with TiH controls. Using Ti 662 chips loaded with D_2 gas as discussed above, we detected a burst of about 360 source neutrons while the sample was warming from liquid nitrogen immersion, at a temperature of about -20°C (Fig. 3b). Later, a burst of 62 neutrons was detected from the sample at room temperature. Agreement was good in both cases in the redundant electronics. The rate of burst observation, two large bursts in about 150 hours of running, is consistent with rates observed deep underground with partially-deuterided samples, so no dependence of rate of large bursts on cosmic-ray flux is in evidence.

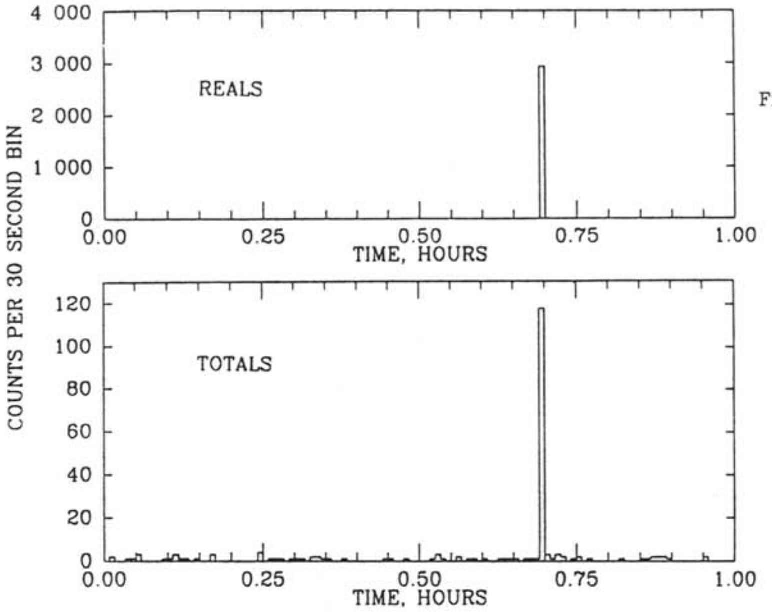


Fig. 3a

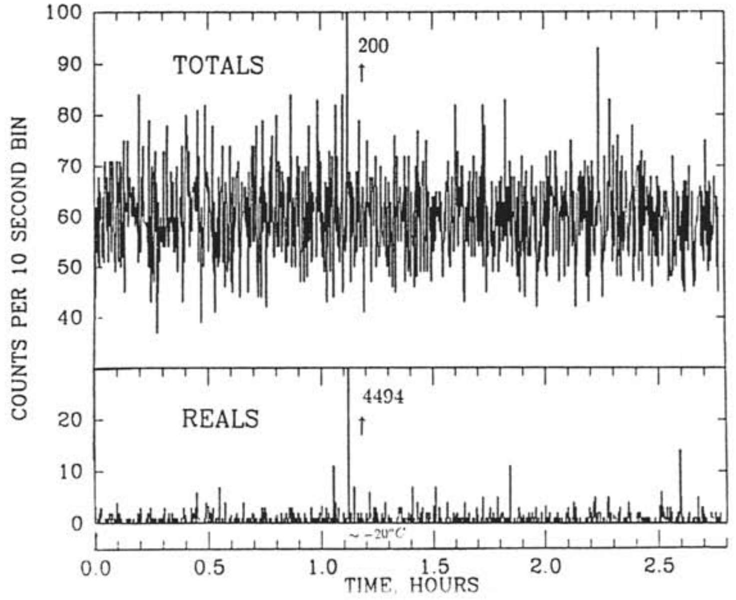


Fig. 3b

Fig 3. Neutron burst events seen in Leadville, Colorado (a) 600 m underground and (b) above ground, using deuterium-loaded titanium alloy described in text. Both bursts occurred during warm-up of the samples from liquid-nitrogen temperature. Burst multiplicities agree within tolerances in the separate registers (REALS and TOTALS registers described in text). Notice that the background levels are **much** lower underground.

Neutron Singles Emissions

We have observed several episodes of statistically significant neutron singles emissions, that is, signals separated by more than 128 μsec that when integrated over time are significantly above background levels. Figures 4 and 5 provide examples of such episodes which occurred in the Leadville, Colorado, mine.

Fig. 4 displays data acquired while three electrolytic cells prepared by Kevin Wolf were running inside the detector. The cells incorporated Pd cathodes and Ni-mesh anodes in a heavy-water electrolyte running at a potential of 2.7 V/cell and a current density of 20 ma/cm2 (approximately; for further details see paper by K. Wolf in this volume). The data are shown in 90-minute bins, with the cell operating out of the detector for approx. 30 minutes before insertion into the helium-3-type detector. Wolf predicted that neutron emissions should occur within the first few hours of running (a long charging-time is not required; this is consistent with earlier neutron observations [1]). About two hours after electrolysis of the freshly annealed Pd cathodes began, the signal rate in the counter jumped to about 120 counts per hour, staying high for about 1.5 hours. At that time, we were obliged to leave the mine so the cells were shut off, removed from the detector, and electrolyte-added for an overnight run. Based on past experience with these particular cells, Wolf predicted that this treatment would end the neutron production. Fig. 4 shows that indeed the signal rate returned to the background level when the cells were re-installed in the counter. Adding to the significance of the increased rate for 1.5 hours is the fact that a small burst (R=1) occurred during this same time interval. A second burst (R=1) appeared during the second run making two bursts in a total of 22 hours of running in the counter. (Recall that only one such burst occurred during approx. 3 weeks of background runs in the same environment.) The neutron source rate implied by these data is 145 n/hr, or 0.04 n/sec (compare with 0.06 n/sec average reported in ref. 1 also using electrolytic cells.)

Fig. 5 shows data taken with deuterium-gas charged cylinders each containing 300g of Ti alloy chips (57% Ti6-6-2, 31% Ti6-4, 12% Ti 10-2-3) prepared at Los Alamos by Mike Paciotti and Howard Menlove as described in the paper by Menlove et al. in this volume (cylinders DD-12 and DH-13 in [14]). Deuterium gas was admitted into each cylinder from a reservoir while the cylinder was inside the detector, and the Ti chips were observed to absorb deuterium both by a drop in gas pressure and by an increase in temperature of the container wall. The data are grouped in 20-hour bins. The second cylinder showed high singles counts for over 20 hours before the detection rate returned to the background level (Fig. 5). No bursts were detected during these runs.

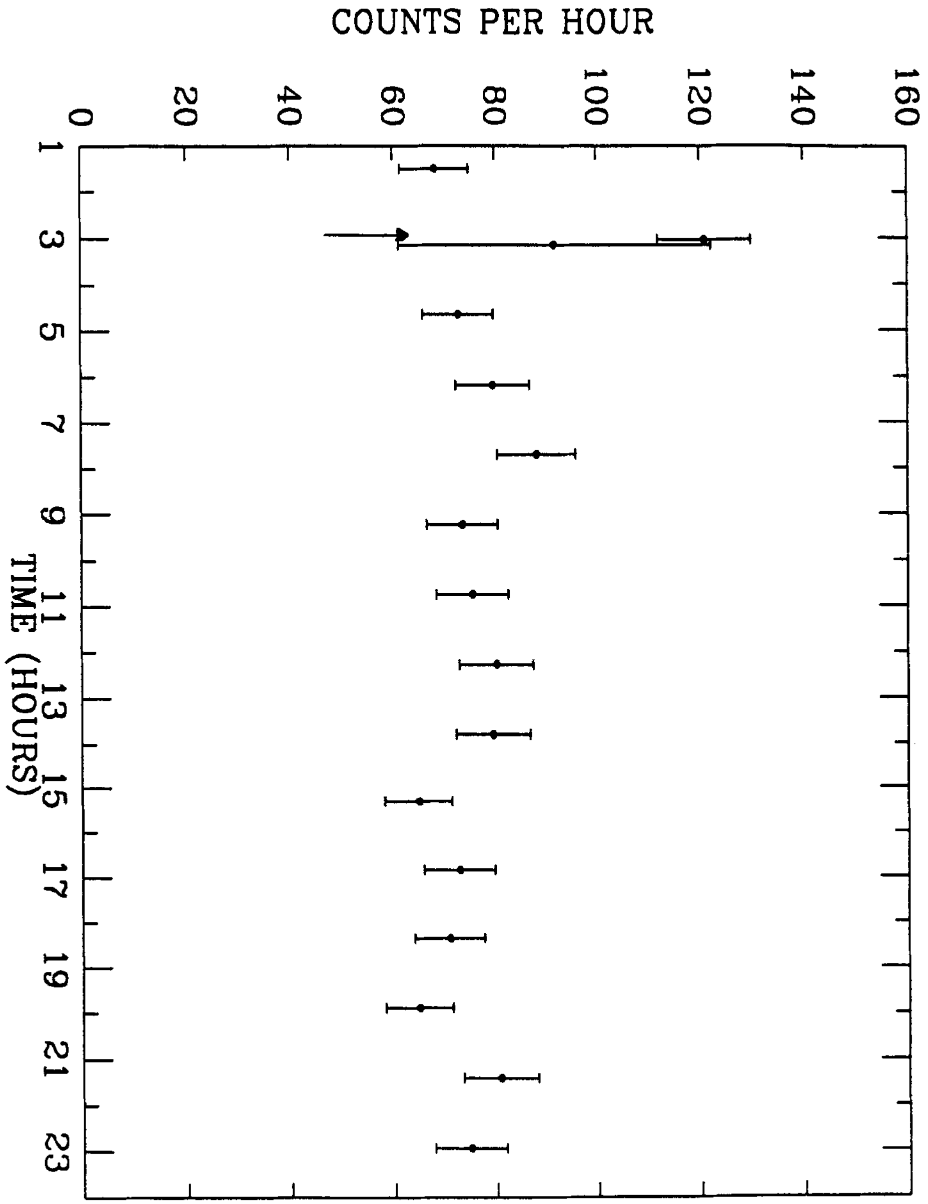


Fig. 4. Data acquired 600m underground in Leadville mine using 16-tube helium-3 type counter and three electrolytic cells operated by K. Wolf. Neutron-singles rates are shown in 90 minute bins, except for 30-minute bin to right of arrow representing time to remove cells and refill with electrolyte. A small (R=1) burst occurred during time marked by arrow, while the rate was high.

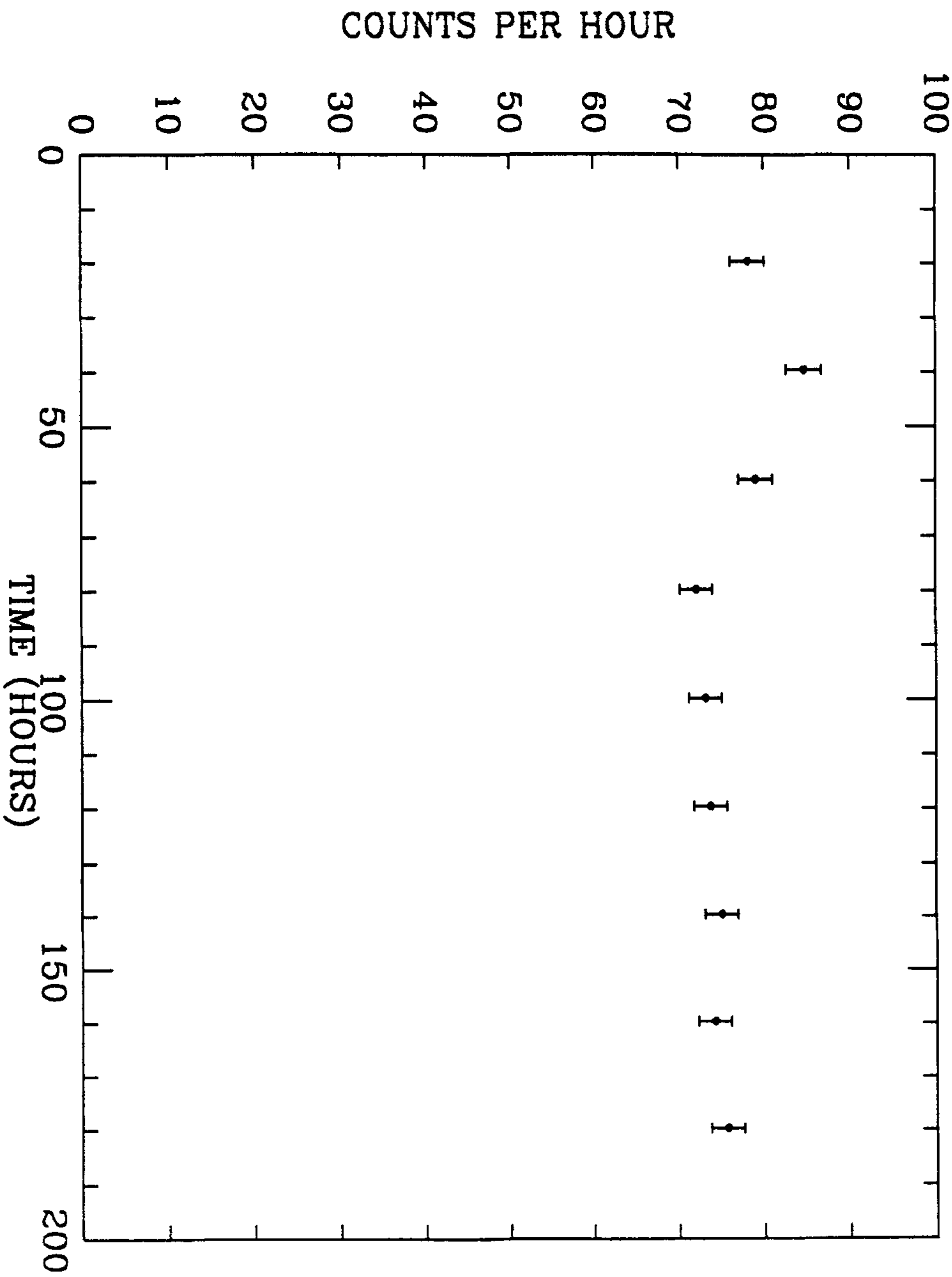


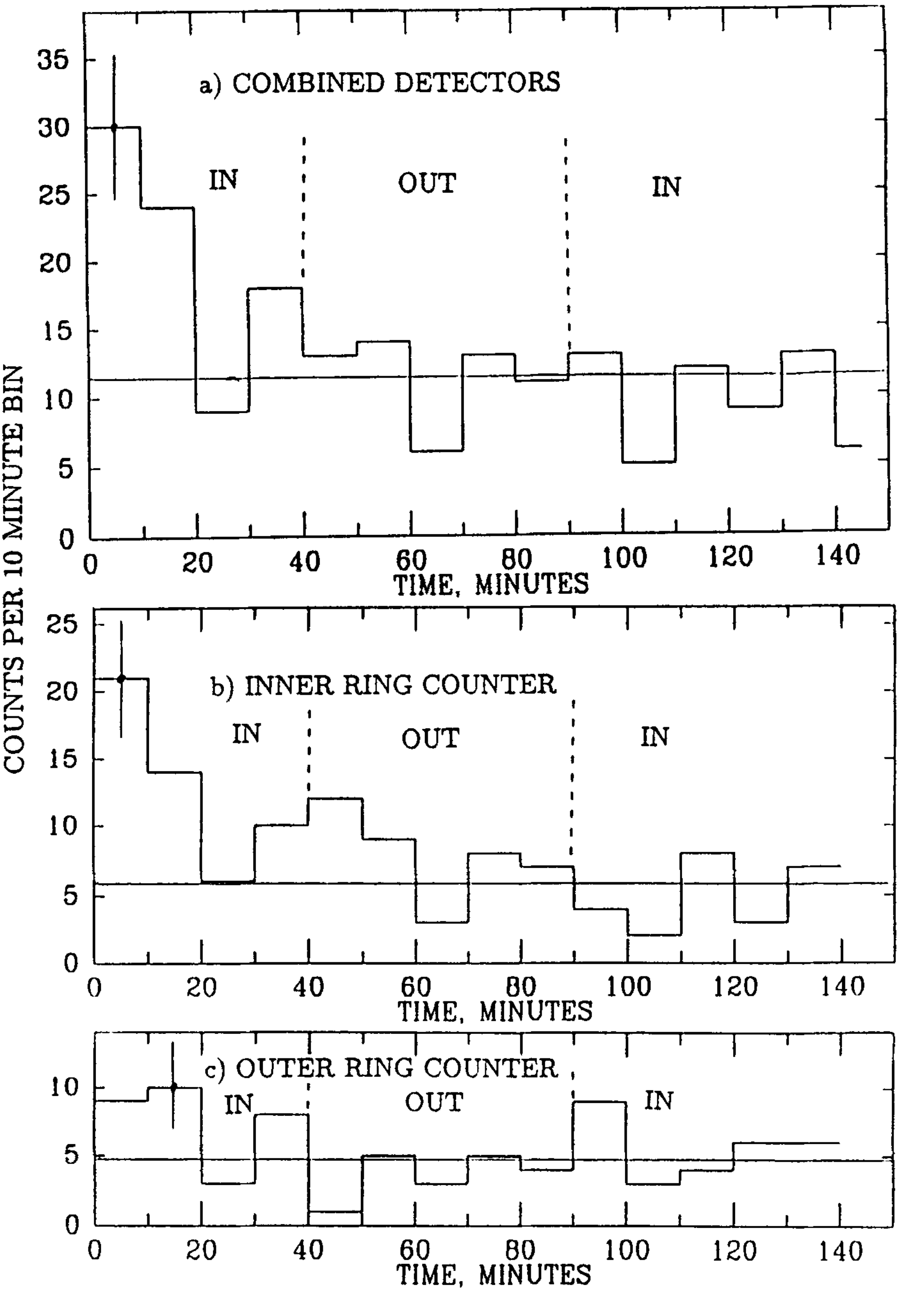
Fig. 5. Neutron-singles rates in 20-hour bins for deuterium-charged cylinders each containing 300g of Ti alloy chips [14]. D2 was admitted into cylinder DH-13B to for first data point. D2 was loaded into DD-12 on second day for remaining data points, so singles-rate was high for some time after deuterium-charging.

The author provided the raw data for Figs. 4 and 5 to a statistician along with additional background which he requested for analysis. He performed the analysis as a "hostile analyst" (his term) since he was concerned about correctly treating largest "peaks" when their appearance is not entirely predictable. Nevertheless, he found the evident peaks in each set of data to be statistically significant; his analysis is described in the Appendix.

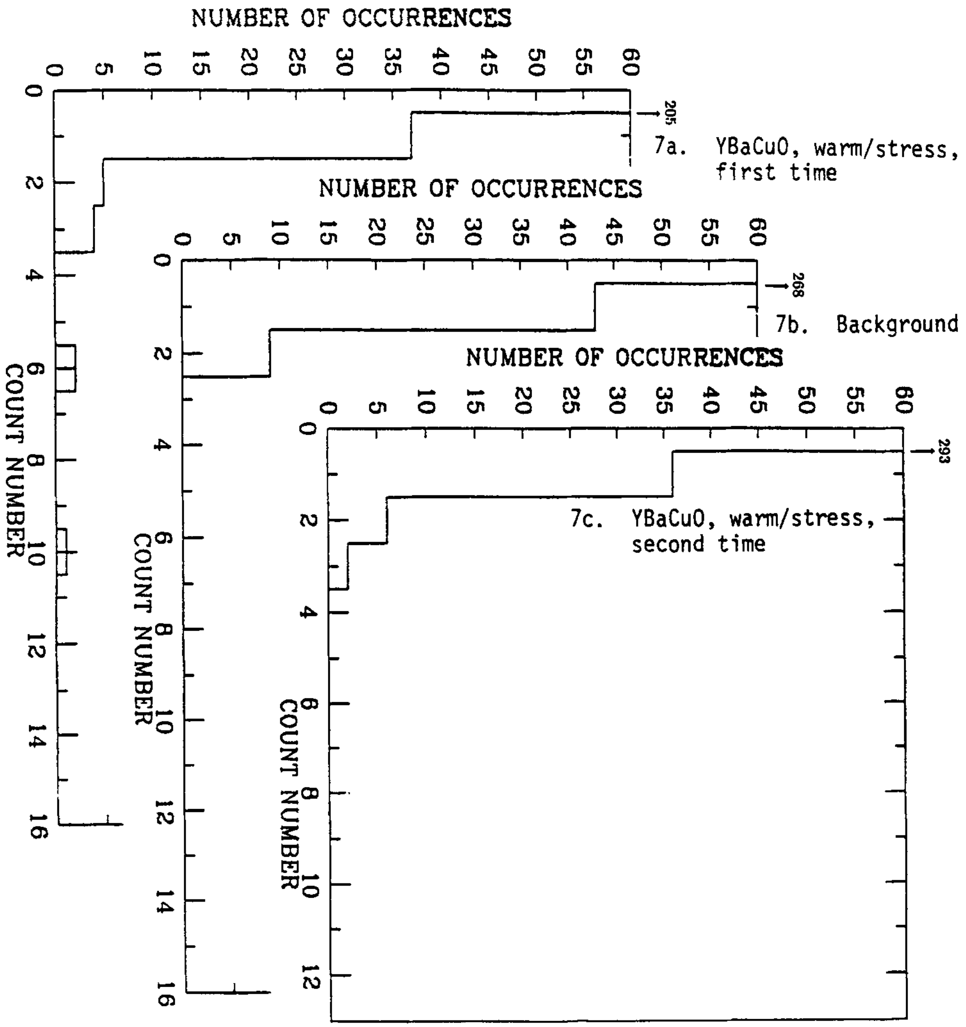
Figure 6 shows data acquired in the Kamioka mine in Japan using the BYU helium-3-type counter. These data are worth noting in that we recorded counts from the inner and outer rings of helium-3 tubes separately and automatically. In this way, we can assess whether any signal shows up in both rings and in the correct ratio for neutrons emanating from a sample inside the counter. Figs. 6a, b show data acquired using a total of 285 g of $Y_1Ba_2Cu_3O_{7-x}$ superconductor material loaded with 0.58 moles of deuterium (75%) + hydrogen (25%). (A mix of isotopes was used since the Kamiokande detector may later be set to search for 5.4 MeV gammas from p-d fusion as well as for neutrons.) The high T_c superconductor came in 2.5cm diameter disks which were broken up to fit into a stainless steel cylinder, heated to 300°C under vacuum, flushed three times with H_2 gas, then pressurized to 10 atm. with the D_2+H_2 mixture which absorbed into the material. In the mine in Japan, we first cycled the partially-deuterided material a few times from LN_2 temperature but saw no evidence for neutron production. Then the samples were removed from the steel cylinder and placed in a cup with liquid nitrogen. Pliers were used to carry a piece of sample into the ^{3}He-type counter where the sample was shattered with the tool. Chips fell into a container inside the detector, and an apparent signal was seen (first 40 minutes of Figure 6). The same data are displayed as a count-frequency plot in Figure 7a showing unusually high counts in several 10-second bins relative to background (Fig. 7b). After 40 minutes, we decided to remove the samples from the detector to be sure that the counter was functioning properly; Figs. 6b and 7b resulted with counts completely consistent with background. The sample was shattered a second time with no significant effect. (Figs. 6c and 7c).

A Poisson was fitted to the background (Fig. 7b) then compared with foreground data (Fig. 7a).[26] The probability is less than 0.0005 that counts over 3/ten-second bin seen in the foreground correspond to the same (Poisson) distribution as the background.

It is important to check the ratio of counts in the inner and outer detectors during the warm-and-shatter stressing of the deuterided material (Figs. 6a, b, c). We find that most of the observed signal is indeed in the inner ring, as expected for a neutron source inside the detector. We expect an inner/outer ratio of 2.0 based on calibration studies with a depleted uranium source versus a ratio of 1.3 found for backgrounds. We found an inner/outer



6. Neutron-singles counts in segmented helium-3-type counter operated in Kamioka mine, 1000m underground, while YBaCuO superconductor with (D_2+H_2) was being simultaneously warmed and crushed inside detector. Counts above background are seen only during first crushing sequence (IN), not when sample was removed (OUT) or when sample was crushed again (second IN). Most counts are in inner ring counter, consistent with neutron source inside counter.



7. Frequency of counts occurring in 10-second bins, corresponding to data in Fig. 6.

count ratio of 2.4 ± 0.4 during the stressing of the deuterided superconductor (Fig. 6a), which is consistent with a source of 2-3 MeV neutrons inside the detector.

We conducted in Japan a similar warm-and-stress procedure using titanium 662 chips and the segmented helium-3-type detector. We prepared at BYU 140 g of Ti662 alloy lathe-turned chips by cleaning following the method developed by M. Paciotti [13,14]. The chips were treated in deuterium gas with repeated warming cycles from LN2 temperature until they absorbed sufficient deuterium to reach approximately $TiD_{1.3}$. The chips were next cooled in a cup containing LN_2. Then, as with the superconductor, chips were taken into the counter with pliers and there squeezed. We observed one burst during the 100 minutes of data-taking, and significantly high counts in one 30-second data-collection interval; the data are shown in Figs. 8a and 8b with similarly stressed TiH (control) chips for comparison. We later processed about 200 g of Ti chips (without deuterium) using the warm-and-squeeze procedure; results were consistent with background.

CONCLUSIONS

A number of procedures have been tried in an attempt to trigger neutron emissions from partially-deuterided materials. We used sensitive, segmented detectors in underground locations in order to make the most definitive tests possible. Redundant electronics allowed us to identify spurious effects with considerable confidence. Neutron emissions that satisfy all tests we have thought of continue to be seen under these conditions. We judge that the best reproducibility came when we warmed partially deuterided high-T_c superconductor and titanium chips from liquid nitrogen temperatures while simultaneously compressing or shattering the materials. This approach builds significantly on other work, particularly that of V. Klyuev [19], F. Scaramuzzi [16], and F. Celani [18] whom we acknowledge. Further tests are needed to confirm the results, in particular to check them in cooperation with an independent group. We have initiated studies with Prof. Yoji Totsuka and his group using deep-underground Kamiokande detector in Japan, a 4500-ton water-Cerenkov system now used for neutrino studies. Tests similar to those conducted at BYU, Los Alamos, and in the mine in Colorado are to be performed in the Kamiokande detector. Results should be available by summer 1991.

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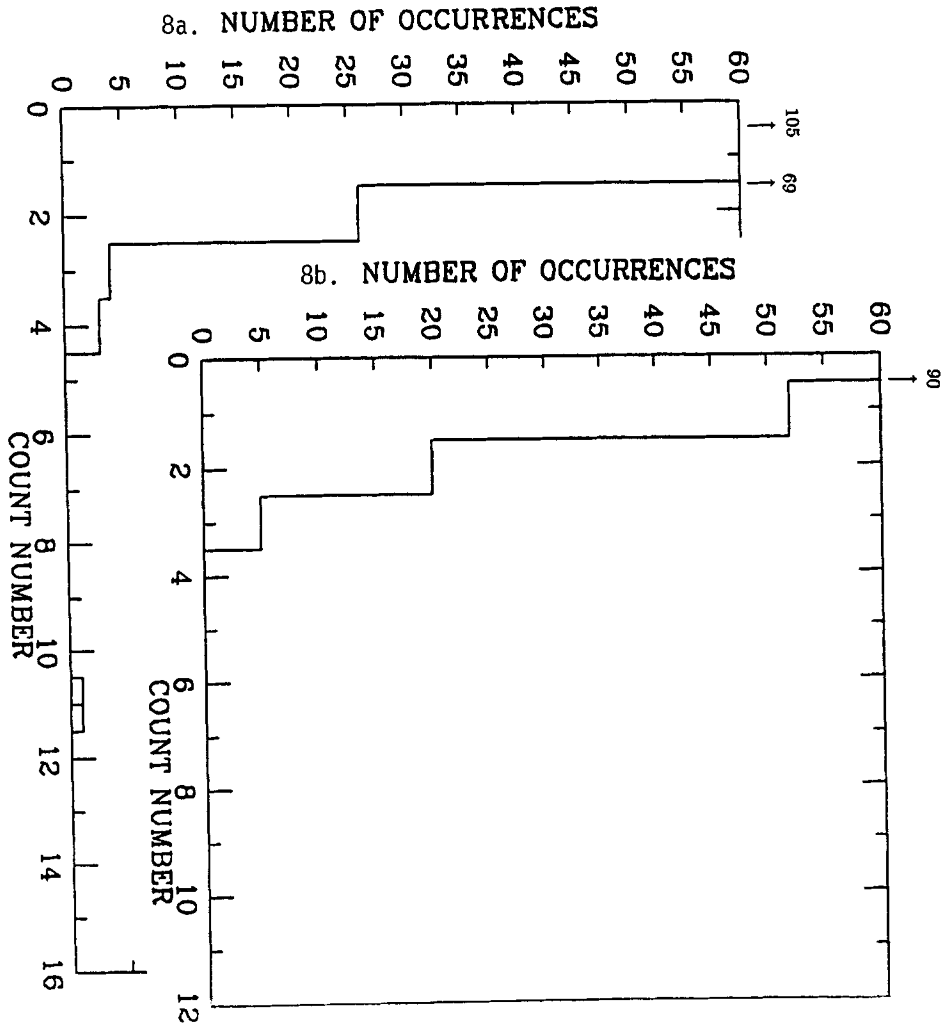

8. Frequency of counts occurring in 30-second collection bins, for a) Ti-deuteride chips (100 minute-run) and b) Ti-hydride chips (82 minute run).

APPENDIX

ANALYSIS OF FUSION DATA FROM COLORADO MINE

by H. Dennis Tolley

Both sets of data (Figs. 4 and 5 in paper) have two common features that must be considered in their analysis. The first is that under foreground conditions, one or more of the observations are expected to be above background. However, not all of the observations are expected to be above the background level. Second, the actual time that these foreground signals will appear is unknown. Thus the analysis will have to include flexibility in identifying one or more observations as significant from background when, in fact many or even most of the observations will be close to or identical to background.

A common error that could be made in analyzing such data is to look for the largest value or set of contiguous values in the experiment and then form a standard confidence interval or a type of "t-test." The major problem with such an analysis is that is does not account for the step that identified the "largest" value. It is well known that the largest value in an experiment does not follow the probability distribution of a random outcome of the experiment. Without adjusting for the step of choosing the largest value, an experimenter can often find a "statistically significant effect" when, in fact, no such effect exists.

The statistical techniques that account for the selection step are collectively referred to as the "multiple comparisons procedures" (see eg., Miller, R. (1966) *Simultaneous Statistical Inference*). The particular procedure used in the analysis is the Dunnett procedure (Dunnett, C.W. (1955) Journal of the Amer. Statist. Assoc. 1096-1121). This procedure compares all possible observations under the foreground conditions with the average of the background conditions.

Analysis of the 90 Min observations. (Fig. 4 in paper)

These data consist of three sets of observations. There are 115 90-minute background observations. In addition there are two foreground runs. The first consist of two 90 minute observations and the second consists of thirteen 90 minute observations. Both foreground conditions are measured as time since instantiation of the foreground conditions (what ever they are such as electrical current, heating or cooling and so forth.) As a consequence, the order of the observations is important.

Assumptions:

1. The actual observations are considered independent over time.

That is, though there may be a temporal trend in the expected neutron counts, the stochastic variation of each count is independent of the variation in counts during any other nonoverlapping interval.

2. The counts are approximately normally distributed. Though the counts would be assumed to be distributed as a Poisson or mixture of Poisson distributions, the number of counts per 90 minute interval is large enough to assume that the distribution of counts can be approximated by a normal or Gaussian distribution.

3. The variability of counts from the mean count for the background is constant over time. This variability is approximately the same as that of the foreground, though the mean value of the counts under foreground conditions may vary over time.

Following the Dunnett procedure, the value of each observation under foreground conditions was compared with the average background count. The background variability was used as the error term for the comparison. Using a type I error probability of .005, only one observation of the entire foreground runs was statistically significant. The significant count was the second 90 minute count of the foreground run (having only two observations, Fig. 2 in text).

The probability that the most extreme observation would be this high if there were no signal is less than 0.005.

Analysis of the 20 hour observations. (Fig. 5 in paper)

This experiment consists of two different foreground runs. The first consists of one 20 hour observation. The second consists of eight 20 hour observations. The background was the same background run that was used in the above analysis. In this case, however, the counts were considered in 20 hour time segments.

The assumptions of this analysis are the same as above. There were three observations in the data that were apparently larger than the rest; the solitary observation in one run and the first two in the longer run. Only the largest of these was statistically significant (p-value less than 0.005). The other two were non-significant (p-value greater than 0.025).

The conclusion is that though three observations were suggestive of an above average number of counts, only the largest count could not be accounted for as chance occurrence of a random count.

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