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Highlights of Papers Presented at the Workshop on Cold Fusion Phenomena Santa Fe, New Mexico May 23–25, 1989

Los Alamos National Laboratory
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FOREWORD

In an attempt to settle the turmoil that followed the March 23, 1989, announcement of controlled nuclear fusion, Los Alamos National Laboratory hosted a three-day workshop on May 23, 24, and 25, 1989, to provide a forum where results of experiments and calculations could be discussed in an orderly fashion.

These proceedings contain highlights of papers presented at the workshop. Some claim observations of excess heat or production of tritium or a few neutrons. Others describe exhaustive, painstaking, unsucessful attempts to induce fusion by methods extracted from sketchy reports. This workshop served to get people who saw no effect together with those who did see effects, in order to hasten a scientific consensus about the reported process. Many such interactions took place in the formal meetings, at late night meetings, in conversations in the hallways, and at the poster sessions. These proceedings claim only to document the salient points of the formal oral papers presented during those workshop days.

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ABSTRACT

This report contains highlights of formal oral papers presented at the Workshop on Cold Fusion Phenomena, hosted by Los Alamos National Laboratory and held May 23–25, 1989, in Santa Fe, New Mexico.

HIGHLIGHTS OF PAPERS PRESENTED AT THE WORKSHOP ON COLD FUSION PHENOMENA

SANTA FE, NEW MEXICO
MAY 23–25, 1989

CONTENTS

Evidence for Excess Heat Generation Rates During Electrolysis of D_2O in LiOD Using a Palladium Cathode: A Microcalorimetric Study

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A microcalorimeter was used to measure excess heat that might be produced by electrolysis of palladium in deuterium oxide. The instrument, based on the Seebeck effect, is capable of detecting approximately 1μW in a maximum heat input of 5 W. Two 5- × 5- × 1-cm cells, one of which contains a heat source and the other a blank, allow accurate differential measurements. Experimental cells were stainless steel containing 7.5–8 cm^3 of electrolyte and were calibrated at the start to ensure that no heat was generated within the cell (as by corrosion or formation of oxide films).

Palladium wires were used as received: some with no preparation, some after cleaning, some after annealing. Some were melted to form spheres. Typically the wires were 0.5 or 1 mm in diameter and 1 cm long; spheres were 2 mm in diameter. Counterelectrodes were 1-mm diameter platinum coils. Electrolytes used were 0.1M LiOD and 0.1M LiOH, both prepared from natural Li metal (^7Li containing ~7% ^6Li), and 0.1 M NaOD prepared from nuclear-grade Na metal.

Electrolysis of LiOH in light water (after an initial charging period) showed no excess heat at current densities of 300, 600, or 1000 mA/cm^2. With 0.1M LiOD, anomalous heat effects were seen, amounting to 16.3–19.3 W/cm^3 Pd, depending on the current density employed. Neutrons were detected in some cells; tritium in some cells, especially those run at low currents. Neither ^3He nor ^4He was detected in the electrodes.

The experimenters acknowledged that their results were preliminary and did not constitute evidence for cold fusion that "would stand up in court," but could not offer a plausible alternative explanation for the excess heat. Recombination of product gases (H_2 or D_2 and O_2), suggested by some, was not observed in parallel experiments conducted outside the calorimeter.

Neutron Emission and the Tritium Content Associated with Deuterium-Loaded Palladium and Titanium Metals

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An experimental investigation was conducted on samples of Pd and Ti loaded with deuterium by the electrolysis of D_2O and by absorption of D_2 gas. In approximately 200 experiments on 25 samples, statistically significant evidence for neutron emission was obtained in 2 separate experiments from 1 Pd-Ni electrolysis cell. Observed rates of 3–4 times the background rate of 0.8 n/min (0.4–2.5 MeV) correspond to a 2.5-MeV neutron source strength of 50 n/min over a period of 1–2 h.

A 3- × 5-in. NE213 liquid scintillator coupled to a 5-in. diameter RCA 8854 phototube was used, for an overall efficiency of 5% for 2.5 MeV neutrons. Pulse-shape discrimination (PSD) was used for n/γ discrimination. Cosmic-ray rejection was provided by the PSD and by 2 ft × 4 ft × 0.25-in. plastic scintillator paddles. Antennas and the PSD were used for external noise rejection. The neutron detector was shielded from the heat produced by electrolytic cells and the temperature was monitored. Data were acquired with a CAMAC-based LeCroy 2280 system interfaced to an 80386 computer.

The presence of 5×10^{12} tritium atoms in the solution of the electrolysis cell was determined several days after the neutron-production runs. Tritium detection was accomplished with a pair of low-noise EMI 9954 phototubes coupled to a 1- × 1- × 3-cm cell. Neutralized samples were mixed with a water-soluble liquid scintillator for an efficiency of 30% in coincidence mode. Energy spectra were compared to tritium standards for the efficiency and for identification through slope and end-point determinations. Tritium content of the cell before neutron production is not known.

Preliminary Investigation of Possible Low Temperature Fusion

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This report describes the results of radiation and heat measurement from a more-or-less "classical" palladium (2.8- × 90-mm)/D_2O(0.2N LiOD) electrolytic cell operated at 28°C in the range 100–400 mA/cm^2. The cell was thermally insulated, was cooled with forced-flow water, and had an internal heater for purposes of calibration. A 1- × 1-in. NE213 scintillator was used for neutron detection (^{252}Cf calibration, threshold set for 1.2 MeV, 0.00146 efficiency). Neutron-produced gamma rays were measured with a NaI crystal with a thermal-neutron shield and a polyethylene converter (1.8–2.7 MeV range, 5.75×10^{-5} overall efficiency). Tests ran for 350–400 hours. The neutron background was ~1 count/hour, but anomalous increases of ~80% were observed, which returned to the ~1 count/hour background when the cell was shut off for ~360 hours. A few points during the long runs showed some increases in neutron counting rate a little above background, but the gamma-ray count at all times remained at background. Generally, the overall energy balance was made to within 100%, with a "little bit

of plus and minus." One incident was reported at about 80 hours into a run, in which excess heat was observed for 4–6 hours, but the totality suggests no long-term energy emission and certainly nothing greater than ~20% in one brief period. A few unexplained temperature excursions of a few degrees were also reported. Measured tritium increases of near twofold were explicable by evaporation during the electrochemical processes. Generally, low-level anomalous neutron and heat production were observed at or slightly above background levels.

Measurement of Neutron and Gamma Ray Emission Rates and Calorimetry in Electrochemical Cells Having Pd Cathodes

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Initial experiments with 6-mm Pd rods were run for 45 to 60 days looking for 30% heat effects (200–300 mW sensitivity) and for neutrons (with a BF_3 counter), with null results. Later experiments featured more accurate measurements, using 1- to 3-mm Pd wires 10 cm long, annealed at 700°C for 1 hour and cooled in vacuum. An isothermal calorimeter (with heaters in the cell to hold constant temperature) was used with temperature control to 0.05°C, giving a detection limit of 15 mW, and 10-day runs were made at 64 mA/cm^2 with matched light-water and heavy-water cells. No differences were seen to a level of 9%, the estimated maximum error.

Off gases showed ^4He at the level found in air, and both ^3He and ^4He analyses of the Pd showed none to the level of detectability. There were no detectable gamma rays; the NaI detector was calibrated with a Pu-Be source. The experiments showed that the signal published by Pons and Fleischman was too narrow a linewidth and did not have a Compton edge, as it should, and as did that reported here. The Pons and Fleischman level of 20,000 $n/s \cdot cm^3$ is 34 times higher than the background of these experiments, and should have been seen but was not. No tritium buildup in the electrolyte was seen; rather, it stayed at the level of 100 dis/min ml.

In Search of Nuclear Fusion in Electrolytic Cells and Metal/Gas Systems

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This paper comprises two pieces of work, an electrochemical effort and an investigation of metal-D_2 gas system. Eleven electrochemical cells were used. All employed palladium cathodes and platinum electrodes. Cathode masses ranged from 2–41 g with surface areas from 3–140 cm^2. Cathode geometries included wires, sheet, rods and tubes. The time was 0.5–28 days. The current density was held at values from 100–140 mA/cm^2. The electrolyte was varied from 0.1M LiOD to 0.5M deuterated phosphoric acid, and the temperature was controlled at selected values between 16 and 50°C. These conditions were believed to bracket those of Pons and Fleischmann. The calorimetry is accurate to 0.1 W. In a typical case, the power in was 5 W and the power out was 5 ± 0.1W. No neutrons above background level were detected.

In the metal-gas experiment, 100 g of titanium sponge was heated to 600°C in vacuum, then exposed to 40 atm of deuterium while it cooled. It was then cooled to liquid-nitrogen temperature. The ^{3}He neutron detectors had an efficiency near 2% for these experiments. These experiments set an upper limit of 4×10^{-25} per cm^2 for the observed neutron flux, much lower than observed by the Frascatti group.

Search for Neutrons from Cold Fusion in Pd-D

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In a search for neutrons from d-d fusion in Pd rods loaded electrolytically with deuterium, three Pd rods were used: (1) 0.125 cm diam. × 9 cm long, drawn and cold-worked; (2) 0.125 cm diam. × 9 cm long, drawn and annealed; (3) 0.41 cm diam. × 8 cm long, cast, drawn and annealed. The rods were held in two electrolytic cells [D_2O (99.5% D) + 0.1 M LiOD, current density 53 mA/cm^2] and placed before a 12.5 cm diam. × 12.5 cm NaI(Tl) detector with a 5-cm polyethylene (PE) moderator interposed. A pair of plastic scintillator plates above and below the NaI(Tl) vetoed cosmic muons. The apparatus was housed within 10 cm of PE surrounded on the outside with lead and borax. Fusion neutrons are moderated inside the PE housing, creating a slow-neutron gas that can be detected by two γ-ray producing reaction signals: (1) n-capture by protons in the PE (2.224-MeV γ); (2) ^{23}Na and ^{123}I n-capture γ-rays in the range 3.5–7 MeV. The latter, produced inside the NaI(Tl), is the more sensitive signal. The background in this region, mostly due to cosmic rays, is far less than the background below 2.62 MeV, which is dominated by natural radioactivity. Therefore, the results are insensitive to ambient natural radioactivity. From the overall neutron detection efficiency (measured with an Am-Be source immersed in D_2O (LiOD) at the counting positions) and the observed background limit, it was deduced that neutron production at the rate of $\sim$ 0.1 n/s in the cell can be detected.

In a four-week measurement $<$ 0.007 n/s·g Pd (0.4-cm diam. rod) were observed compared to 10^3 n/s·g Pd claimed by Fleischmann and Pons for a similar Pd rod. This result implies $< 2.2 \times 10^{-24}$ d-d-n fusions per dd pair per second in the Pd electrode, as compared to 10^{-24} to 10^{-23} observed by Jones et al. in a Ti electrode.

Calorimetry, Neutron Flux, Gamma Flux, and Tritium Yield from Electrochemically Charged Palladium in D_2O

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This work features sensitive nuclear detection equipment and calorimetry at the 6% level, with no detectable heat excess or nuclear products from electrolytic cells. A variety of error sources are described. Neutron detection used 12 ^{3}He proportional counters with about 24% efficiency, with cosmic ray veto. Nothing above background was seen. The Pd wires ranged from "as received," to annealed, to cast in alumina, and some runs extended to almost 600 hours. The results place a neutron limit at 10–100 neutrons/hr·cm^3 Pd. There were no gamma rays to the limit of 100/h as determined by a 15-cm cube of NaI. Tritium buildup and ^{4}He in the off gas were similarly negative. The calorimeter is a Tronic unit similar to the Texas A&M unit (Appleby, Srinivasan) but it was used in a constant temperature (to 0.001°C) mode. Power input by electrolysis is compensated by a power decrease in an internal resistor, and $(V - 1.54)I$ is always the measured decrease in resistive power, to the 6% level.

Continuous calibration of the rate of heat loss was done, to ensure that changes in that loss were not interpreted as excess heat. The paper gives compelling reasons why open-calorimetry results are not sufficient for believing heat excesses at the 10% level, which is the level in all experiments in the U.S. where heat output is claimed.

Search for Fusion in Deuterated Transition Metals: Dynamical Pressures Above 1 Megabar

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A cylindrical shock experiment was performed on deuterated Pd (0.3 g) and Ti (0.1 g) foils using a well-tested fully recoverable, high-pressure design. Four grams of Zn was placed in the experimental chamber as a post-shot neutron radiochemical detector. The system was pressure tested and its free volume was measured. It was then cleaned to remove gas contaminants, surface poisons, or deuterium transfer inhibitors, and back-loaded with deuterium at room temperature. The initial pressure was 50 psi, which dropped to 30 psi of deuterium gas. The observed uptake rates showed that both Pd and Ti foils deuterated to a deuterium-to-metal ratio of about 0.7. The sample container was removed from the loading system, maintaining gas tightness, and inserted into the high-explosive configuration. The entire system was then subjected to a dynamical shock pressure of more than 0.1 TPa. Prompt neutron detectors were placed behind protecting sandbags and Pb bricks close to the experiment. Post-shot radiochemical analysis was also performed. The results showed that less than 10^4 neutrons were generated. No increased neutron flux above background was detected during the several microseconds of dynamical pressure on the deuterated foils. It was concluded that mechanisms to enhance fusion rates in deuterated transition metals were not present at the detection level and pressures of this experiment.

Test for "Cold Fusion" in the Pd-D_2 and Ti-D_2 Sytems at 350 MPa and 195–300 K

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Experiments are in progress on the Pd-D_2 and Ti-D_2 systems at 350 MPa and 195–300 K, to investigate the possibility that "cold fusion" occurs in high D/metal phases generated by pressurization with D_2 gas. Reactions between high-purity Pd or Ti and D_2 are being monitored using BF_3 neutron detectors and thermocouples. The neutron-detector array has an efficiency of ~6%, as determined using a ^{252}Cf source. The pressure vessel and neutron detectors are immersed in a water bath thermostated at 300 K. A type K thermocouple in contact with the Pd or Ti sample is compared with a reference type K thermocouple also housed in the vessel and located ~10 cm above the sample. The neutron flux, gas pressure, and thermocouple and bath temperatures are continuously monitored at time intervals ranging from 6 s to 5 min.

Experiments completed to date in the Pd-D_2 system at 300 K have shown no neutron flux significantly above background (9.5 ± 0.5 counts/min), and no sustained heat production has been detected.

The rationale for these studies was to investigate the possibility that electrolysis is not required to induce cold fusion and that charging palladium by deuterium under high pressure might produce effects similar to those observed by Fleischmann and Pons and others.

No neutron flux above background was detected under any sets of pressure/temperature/time conditions investigated in either system.

Measurements of Heat, Neutron and Gamma Flux Induced by Muons Stopped in Deuterium Saturated Targets

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Work in progress explores what happens when a flux of muons is put into metal hydride targets saturated with deuterium. The experiments are designed to measure the number of neutrons generated for each muon stopped by the hydride, and to determine what happens to the muons: whether they are captured quickly by the heavy-Z nucleus, or whether there are significant effects related to the presence of deuterium atoms and/or shielding of metal nucleus.

A pulsed beam of protons from Brookhaven's alternating gradient synchrotron was directed against a 3-inch-thick Pd target to generate pions that then decayed to muons. Both the pions and the muons were momentum analyzed with bending magnets before reaching the target area. When muons that passed through 3 scintillation detectors and 1/8 inch of lead were not seen leaving the target, various detectors were triggered to measure neutrons (BF_3 / ^3He counters), gamma rays (NaI crystals), or heat (calorimeters) emitted by the target. The neutron detectors were calibrated with californium and americium-beryllium sources and typically have 1.5% efficiency.

Targets were of three types: pressure-formed (at ~200°C and ~200 psi for 10 hours) hydrides of palladium, vanadium, titanium, and lanthanum with a D/metal ratio typically of 0.7; electrolysis-formed hydrides of swaged and annealed palladium (the latter with 1- to 2-mm crystallites); and frequent control targets (air, heavy water, palladium, lead, and deuterium gas). The relative rates will be measured with or without muons for cast thin Pd rods in an ongoing electrochemical cell similar to that used by Pons and Fleischmann.

Because of the continuing nature of the work and the limited time, only cautious statements were made about results and no numbers were given (e.g., for the upper limit on the number of neutrons per stopped muon).

High Precision Calorimetric Search for Evidence of Cold Fusion

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This paper describes a precision calorimeter with catalytic conversion of the off gases to water, thus eliminating the need to account for vapor transport in the power balance. Cells were calibrated with resistors for absolute accuracy, for temperature gradient effects when the calibrating heat was localized to different corners of the cell, and for response time. It was determined that the cell was 100% efficient in recombining D_2 and O_2, that it was completely insensitive to thermal gradients, and that the absolute accuracy was 0.3%. A Pd rod of unspecified parameters was loaded with D_2 and run for 12 days at 40 mW/cm^2. To the level of 1 mW per gram there was no excess heat. The experimenters offered to run cells prepared by others in their setup.

Nuclear Reactions and Screened-Coulomb Fusion Rates

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The R-matrix approach to nuclear reactions, a very convenient way to describe a many-body system with interacting particles that have both long- and short-range forces, was briefly discussed. The results of this approach were shown for the calculation of branching ratios, reaction constants, etc., for the nuclear reactions of hydrogen isotopes. The theory included nuclear effects at small distances, allowing the rates for a variety of screened Coulomb potentials to be calculated more correctly.

Among the findings for the deuterium-deuterium reactions was no evidence for a strong enhancement at lower energies of the proton branch due to something analogous to the Oppenheimer-Phillips effect. The calculations also predicted quite different branching ratios for the d + d reactions when they were initiated by S-waves than when they were initiated by P-waves. Also, because the amount of screening necessary to get a 10^{-24} fusion rate was found to correspond to unreasonably high electron densities, it would appear better to look for processes that produce higher energy interaction ions rather than screening effects.

Molecular Dynamics Simulation of $PdD_{1.1}$: How Close Can Deuterons Get?

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A molecular dynamics simulation of palladium deuteride was discussed that gave a distribution of distances for neighboring deuteriums. The deuteride considered was "above stoichiometry" to increase the chance of deuteriums crowding together, especially by multiple occupancy of octahedral sites in the palladium lattice. The calculations used strictly classical dynamics, so any exotic quantum effects would not be seen.

The calculations showed that double occupancy of the octahedral site occurs only if very short screening lengths (one-quarter of a Bohr radius) are used. At one-half a Bohr radius, double occupancy becomes metastable (there is a stable-like energy, but it lies well above the energy for one deuterium in an octahedral site and another in a tetrahedral site). At one Bohr radius there is no minimum at all.

All distributions calculated (for temperatures of 300 and 1300 K and palladium-deuteron potentials for the tetrahedral site being both stable and unstable) showed no approach closer than that in a D_2 molecule. For example, at 1300 K, distances down to 0.7Å occur, which corresponds roughly, for some small fraction of the time, to the atoms getting as close as in a D_2 molecule, but no closer.

Conditions Leading to the Production of Cold Fusion Neutrons

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Conditions were discussed that must be attained with the metallic lattice to achieve the $d + d \rightarrow {}^3He + n$ fusion rates observed by Jones et al., supposing that the so-called "cold fusion" is occurring in small pockets of deuterium under plasma conditions. The particular mechanism considered responsible for the formation of the pockets is the catastrophic collapse of microscopic cavities between the metallic crystals, caused by the sudden expansion of crystals under stress. The collapse achieves lukewarm plasma conditions (temperatures of the order of 10 KeV).

Using conventional physics (such as barrier penetration tunneling with the WKB approximation) for $Z = 1$ systems, fusion cross sections were calculated as a function of energy, then fusion rates were obtained from a thermal average of cross sections. Such averaging involves essentially two exponentials: one expressing a probability of occupying a given energy state, which rapidly decreases with energy, and one due to the tunneling probability, which increases steeply with energy. The competition between these two factors results in a Gamow-Teller peak that reaches a maximum very high above the working temperature. The implication of this analysis is that the entire fusion amplitude is coming from an energy that is much higher than the temperature.

The fusion rate of 10^{-23} needed to explain the results of Jones et al. can be achieved with a screening length of 0.1Å, which is very small and essentially unrealistic. In addition, only a very small component of the deuterium in the metallic lattice will be in the high-temperature phase when the cavities are collapsing. Thus, screening is unable to explain, in terms of conventional physics, the observed fusion rates, and some resonance or off-equilibrium behavior will need to be invoked.

Third Plenary Session (C): Neutron and Gamma-ray Spectroscopy

Cold Nuclear Fusion in Condensed Matter: Recent Results and Open Questions

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The realization that muon-catalyzed cold fusion had serious fundamental difficulties (i.e., alpha-particle/muon sticking and termination of the catalysis chain) prompted the BYU group in 1985 to examine alternative approaches to cold fusion. It was realized four years ago that the increased density of hydrogen in metallic solids would lead to enhancement of fusion rates to a level that might be measurable. This history, together with the anomalous excess (by $\sim$1000) of ^{3}He near (volcanic) terrestrial hot spots, launched the BYU group on its present course of research with an emphasis on searching for fusion products from metals that have been heavily infused with deuterium by electrochemical methods. A central guiding principle in this research has been the need to achieve highly non-equilibrium conditions in the hydride. After settling in 1986 on electrolysis as a means to create a non-equilibrium infusion of hydrogen, even after examining pressure-loading methods (but unfortunately without cooling the pressure-loaded samples), an effort was launched to develop a sensitive neutron spectrometer based on coincidence-counting neutron events occurring in water and lithium-doped glass media; it is important to identify the 2.5-MeV neutrons from the DD fusions to determine whether fusions are in fact occurring. Several man-years of effort were required to develop and calibrate the sensitive neutron spectrometer that has provided the main statistical evidence for low-level cold fusions occurring in the BYU electrochemical experiments. Recently, the BYU effort has expanded to include involvement in electrochemical and pressure-loading experiments at Los Alamos and pressure-loading experiments at the Italian Gran Sasso.

As for most of these measurements, the neutron counting for the BYU electrochemical cell experiments is an exercise in low-level counting statistics, with statistically significant results being characterized by $\gtrsim$5 standard deviations; typically a little more than twice as much background data were taken as foreground data. Over a series of neutron-counting experiments, the average 2.5-MeV neutron count rate was 0.06 counts/s, the maximum was 0.40 counts/s, and statistically significant deviations in the counting rate over the ensemble of runs was reported. The count rate with the greatest statistical significance (0.4 counts/s) was seen in February 1989 and has not been repeated. Even though no statistically significant neutron counting results were observed with either a deuterium electrochemical cell with no current or a light-water cell, the possibility that the statistically significant 2.5-MeV count rate is "artificial" cannot be ruled out. What can be ruled out is the origin of these neutrons being catalyzed by muons of cosmic origin. The original "Mother-earth soup" used by the BYU group has generally been replaced with a simpler electrolyte (palladium chloride, lithium sulfate), and statistically significant neutron count rates of 0.04 counts/s are being observed.

The BYU group is collaborating with the Los Alamos groups working on both electrochemical and pressure-loading deuterium infusion experiments; the latter is described in a separate presentation (Menlove). The electrochemical tests are being monitored for neutrons using a

17%-efficient ^{3}He proportional counter with a background level of ~0.37 counts/s. At about 3 standard deviations, the neutron source is estimated to be ~0.08 counts/s. Some neutron bursts were observed from electrochemical cells (53 neutrons in 128 μs), as for the pressure-loading experiments; neutron bursts were observed after the current was reduced to zero, but not after the cell was removed from the detector. Generally the ~0.1 counts/s count rates for the Los Alamos cells are similar to those reported from BYU and from Texas A&M (Wolf). Generally, excess heat was not observed, and the excess-heat experiments appear to be distinctly different from those showing radiation; a lack of recognition of this difference really has created much confusion. Expression of this difference in terms of a dramatic shift in the DD fusion branching ratios flies in the face of hard experimental (e.g., muon-catalyzed fusion) and theoretical (R-matrix calculations) evidence; the origin of excess heat from nuclear-fusion processes was strongly challenged. Rather, piezonuclear fusion or fracto-fusion were offered as two plausible explanations.

It was concluded that:

(a) energy applications are a long way off ($\lesssim 10^{-13}$W/cm^3);
(b) geophysical ^{3}He and heat production might be explained, and
(c) new physics and chemistry (nuclear, electro-, solid-state, geophysical) warrant continued research.

Experimental Evidence for Cold Nuclear Fusion in a Measurement Under the Gran Sasso Massif

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The results of neutron emissions from electrochemical cells using titanium electrodes and a BYU "Mother-earth soup" type electrolyte in the low-background Gran Sasso Massif were reported. The work was performed in collaboration with the BYU group. The Italian Gran Sasso Massif Laboratory is under 1400-m Mount Aquila, where in the 20 x 100 x 18-m experimental halls the natural radioactivity background is reduced tenfold. Furthermore, the cosmic muon flux is reduced by millions from that at sea level. The most significant background is attributed to gamma radiation, so a two-detector system (one for the electrolytic cell and one 8 m from the test cell for background) was designed with a 10^{-4} gamma-ray rejection efficiency; the neutron background was measured to be 0.08–0.16 counts/s. Proton-recoil scintillations were used as neutron detectors with a high gamma-ray rejection rate; the energy resolution of these NE-213 liquid scintillation detectors was 28% at 0.77-MeV electron equivalent energies. The combination of low background and the more-or-less-standard detectors should allow measurement of neutron rates of the order of those measured by the BYU group. With a fixed gamma discrimination level, the background measurement was made with the separate detectors before and after each ~1-hour electrolytic-cell neutron measurement. After about 1 hour of electrolysis, the neutron count rate increased to a maximum and then decreased to the background level after ~3 hours; this behavior was observed in two subsequent tests. Movement of the electrolytic cells to the background detector produced an increase in the neutron counting rate. Monte Carlo analysis of the detector amplitude verified that the neutron energy

spectrum is comparable with the 2.5-MeV DD-fusion neutron. These computations predicted a detector efficiency of $(4 \pm 0.6) \times 10^{-2}$ for the 2.5-MeV DD-fusion neutron. This calibration led to the estimated 2.5-MeV emission rate of 0.25 counts/s. Scaling this emission rate for the differences between the cells used here and those used by the BYU group gave 0.33 counts/s, which is close to the BYU value of 0.4 counts/s. Hence 2.5-MeV neutrons were observed following electrolytic infusion of deuterons into titanium cathodes (gold anode), which confirms in magnitude the BYU neutron-emission results but with statistics that are twice as good. Future work will focus on further reducing the gamma-ray background, performing systematic "blind" measurements, and attempting to observe gamma rays from the Pd fusion reaction.

The Measurement of Neutron Emissions from Ti plus D_2 Gas

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The results of neutron measurements on D_2 pressure-loaded metal samples were reported, wherein both random (no time correlation) and burst (time-correlated) neutron emissions were observed. Four different neutron detectors were used, typical of which was a high-efficiency array of 16 ^{3}He tubes embedded in polyethylene; these detectors were highly insensitive to microphonics (Testacoil), gamma rays (1 r/hour source), temperature (0.01%/K), and instabilities (1% per month drift). Typical detector efficiencies were in the range 19–34%. The test space was three floors below ground and shielded overhead by ~1 m of concrete. The pressure cylinders (25 cm long, 2 cm in diameter) containing a mixture of palladium and titanium shavings were loaded with pressurized deuterium (20–50 atm), cooled to liquid-nitrogen temperature (10–30 min), placed in the room-temperature neutron detector (2–3-hour natural warmup period), and, along with an adjacent background detector, were monitored for neutrons.

Neutron counts were stored in 1000-s time bins, with time zero being the removal from the liquid nitrogen bath and insertion into the neutron detector. Substantial bursts of counts (~100, accounting for detector efficiency) were observed when the cylinder was first removed from the liquid nitrogen bath. The pressure cylinder had to experience several thermal cycles before neutrons were detected. No neutrons were observed from a dummy cylinder. About 1 hour into the warmup cycle, when the pressure cylinder was at –30°C, high neutron counts (~85) were observed, followed by smaller bursts. This behavior could be reproduced for five to six thermal cycles. It was observed that the point of maximum thermal stress (highest time-temperature change, highest gradients) are at zero time and not when the "–30°C" neutrons are observed. Time-uncorrelated (random versus burst) neutrons were also observed, with differences between dummy and sample pressure cylinders in neutron count rates amounting to 11 standard deviations; this was reduced to 4 standard deviations when dummy and sample cylinders were switched between detector systems. The rate of random neutron emission ranged from 0.05 to 0.2 counts/s, which is similar to the results from BYU and the Grand Sasso Massif Laboratory. The time-correlated neutron bursts, which ranged from 10 to 300 neutrons over ~15 events and occurred in ~100 μs, could be the result of "fracto-fusion" events or other mechanisms. The identification of materials (titanium alloy), neutron-energy spectrum, alloy microstructure detail, and gas (deuterium, tritium) are areas where future activities are being targeted.

Neutron Emission from a Titanium–Deuterium System

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The very earliest (and exciting) phases of these "ground-breaking" pressure-loading experiments at Frascatti are reported, along with results from two even more preliminary experiments, one by Magrini at Frascati and one by Mazzone and Vittori at Casaccia.

The idea of achieving nonequilibrium deuterium concentrations in metals by gas-phase high-pressure injection, rather than the more complex (and possibly elegant) electrochemical-infusion methods, was pioneered at Frascati. Using ~100 g of titanium shavings, a series of pressure-loading (~50 atm) and temperature cycles was tried and tested in an apparatus that contained no more than a pressure cell, a thermocouple, a container of liquid nitrogen, and an array of (three) BF_3 neutron counters (0.005% efficient, inferred from presentation). After room-temperature D_2 pressurization, the test cell was cooled to liquid-nitrogen temperature and then, since no neutrons were observed, allowed to warm slowly up to room temperature by allowing the liquid nitrogen to evaporate [unlike the Los Alamos experiment, which removed the test cell from the liquid nitrogen and commenced a rapid (few hour) warming schedule]. The first burst of neutrons was observed post facto when a weekend check of the nitrogen revealed a low level and an unobserved (real-time) neutron burst. Neutrons were again observed later, when liquid nitrogen was removed to perform an electrical check, thereby allowing the sample to warm again; this sequence constituted the "first test" where neutrons were observed. The second neutron event occurred while slowly increasing the sample temperature from liquid-nitrogen temperature and pumping (10^{-2} torr) on the specimen; a particularly high neutron emission was observed (~5000 n/s, compared with 270 n/s for the first event in a background of 6.7×10^{-4} counts/s, equivalent to 13 n/s). The third experiment in which neutron emission was observed first cooled the titanium to liquid-nitrogen temperatures and then admitted deuterium at 20 atm; neutrons were observed one hour after introduction of D_2 at a rate of ~200 n/s.

The "search and try" nature of these preliminary experiments, the randomness and unpredictability of success, and the spirited search for explanations is evident. The possibility of counter saturation and neutron-burst time limitations/distortions by neutron slowing-down time in the detector are also apparent and noted.

The other Frascati (Magrini) experiment used titanium sponge, pressure-loaded and cooled to liquid-nitrogen temperature; with simultaneous warming and pumping on the sample, the experimenters began to measure "a little excess neutrons" after ~10 hours. The Casacci (Mazzone and Vittori) experiment heated titanium blades at 1000°C in the presence of ~0.1 mbar of D_2 and then decreased the temperature to 500°C at 20 mbar D_2; neutron emission was observed soon (1 min) after this sample was heated to 1000°C again.

While these "look and see" kind of experiments and the apparent success of neutron generation are exciting, considerably more systematic work with expanded diagnostics and better materials characteristics are needed before these interesting observations can be explained.

Upper Limits on Emission Rates of Neutrons and Gamma Rays from "Cold Fusion" in Deuterided Metals

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A search for neutrons and gamma rays emitted in "cold fusion" in electrolytically deuterided metals was carried out with a very low background and a sensitive neutron-detection system comprising an array of six liquid-scintillator neutron counters operating in coincidence, with a total efficiency of 1%. Pulse-shape, pulse-height, and time-of-flight measurements were made for scattered neutrons. Gamma rays were detected in two large (12.5-cm) NaI(Tl) detectors with a total efficiency of 0.1% at 5.5 MeV. The detection system was shielded from background radiation and two large-area cosmic-ray veto counters were used. Up to four electrochemical cells, similar to the ones used by Fleischmann, Pons, and Hawkins and by Jones et al., ran concurrently. Palladium or cold-worked titanium rods were used as cathodes. Some of the electrode material was cold worked, some was annealed at 1000°C in flowing argon, and some was vacuum annealed. Most of the electrodes were anodized (i.e., operated with reversed current); some were pre-charged with deuterium. The metals were electrochemically charged with deuterium in heavy water (97.5% or 99.8% D_2O), electrolytes containing LiOD, or a variety of salts. Some electrolytes were intentionally poisoned with water, some were very pure heavy water, and some used the BYU "Mother earth soup." Titanium alloy powder deuterided at room temperature and high pressure was also used for comparison. No statistically significant deviation from the background was observed in either gamma-ray or neutron detectors over a period of 3 weeks. The gamma-ray detector background was one count per hour per channel in the region where the DD gamma ray is expected. Using a californium-252 neutron source, the gamma-gamma scattering occurs within 0.6 ns, which is within the time resolution of the detector (~2.5 ns). The (n,n') scattering is separated by 13 ns for californium-252 and 10 ns for Pu/Be neutrons, with the expected energy scaling being reported; these calibrations indicate that the detector is working with nearly 100% resolution. This detector system gave a background of 1.7±0.5 counts per hour, which was claimed to be much lower than most other detectors being used to search for cold-fusion neutrons. It was also claimed that this level of pulse-height-discriminated, time-of-flight-selected background ($\lesssim$1 count per hour) was needed "before we can make any conclusive statement" about cold fusion. The grand total of all Yale/Brookhaven experiments was, "no effect."

Specifically, the rate of "cold fusion" of d + d in the Pd and Ti samples was estimated to within 98% confidence level to be smaller than the order of 10–25 fusions per atom pair per second (30 upper limit). The estimated neutron flux in the experiment is a factor of 50–100 smaller than that reported by the BYU group, and some million times smaller than that reported by the Utah group. In spite of the impressive sensitivity and care that characterized the neutron-detection methods reported by the Yale group, the information given on the electrochemical aspects of this study was not sufficient to exclude that aspect of the test as the cause for "no effect."

Lack of Neutron and Gamma Radiation from PPL's Cold Fusion Experiments

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A variety of attempts to reproduce the various "cold fusion" experiments have been made, along with some variations on their basic themes. To date, no evidence has been derived from any Princeton experiments for the production of either neutrons or gamma rays at rates above background. Experiments performed include: (a) electrolysis in a pure D_2O cell with 1M LiOD or LiOH solution and various palladium cathodes at current densities up to 0.06 A/cm^2; (b) electrolysis in a 50-50 D_2O-H_2O cell with a graded drawn Pd wire (or cast Pd sphere) cathode at current densities up to 0.05 A/cm^2; (c) thermal and pressure cycling of various high-pressure D_2-gas-loaded Ti turnings, Ti powder, a Nb bar, and mixtures of alumina, quartz, and feldspar. The potential advantage of using a mixture of light and heavy water is to generate the more easily detectable 5.5-MeV gamma ray; generally, gamma rays from the less reactive Pd fusions are expected to give higher count rates.

For all the experiments, neutrons were measured with BF_3 proportional counters and gamma rays were measured with NaI scintillation detectors; these measurements were made at different times and at separate test stations. The neutron monitoring station was shielded with a polyethylene moderator and cadmium absorber, and the background count rate was found to be highly variable (530 counts/hour). The neutron detection efficiency was determined with a ^{252}Cf source to be 1% for experiments (a) and (b) and 0.1%, 0.3%, or 1% for experiments (c), depending on configuration. The gamma-ray station employed a NaI scintillator and photomultiplier system that was closely coupled to the electrolysis cell; this detector consisted of a NaI cylindrical annulus fitted with six photomultipliers. The central and surrounding detectors were operated in anticoincidence mode to minimize spurious signals from external sources. Surrounding this cell/detector array was lead shielding to reduce the background further; the background rate was 515 counts/hour in a 1-MeV-wide window around the 5.5-MeV region of interest. The gamma-ray detector energy calibration was determined with ^{60}Co and ^{137}Ce sources. Hence the neutron-counting apparatus was capable of continuously resolving a neutron source strength of $\sim$1 n/s, and the gamma-ray counting apparatus is capable of resolving a gamma source strength of 1 photon/s; this apparatus, however, could not detect neutrons as low as the level reported by the BYU group.

Theoretical efforts considered both proton- and deuteron-induced nuclear reactions with the various isotopes present in the electrolysis apparatus. No bound excited states exist in ^{4}He, and only three unbound excited states lie below the d + d reaction threshold. The width of the lowest-lying excited state (19.8 MeV) is 0.27 MeV. The higher excited states are broader and overlap strongly; therefore one would expect the nearly prompt ($\sim 10^{-20}$s) decay by particle emission from the compound ^{4}He nuclei rather than an electromagnetic mode of decay. Only two mechanisms for "cold fusion," therefore, are considered: (a) tunneling through Coulomb barrier by cold deuterons, and (b) cold-target bombardment by deuterons accelerated within the solid in bursts through electric fields generated (perhaps) at fractures. The fusion rates for tunneling in p-D, D-D, and D-T molecules have been computed. The dependence of fusion

rates on electron mass and temperature was determined. This work suggests that, if electrolysis experiments of Fleischmann and Pons and others were repeated with mixtures of hydrides and deuterides, the relative importance of quantum-mechanical tunneling versus simple cold-target bombardment could be determined.

An Attempt to Measure Characteristic X-Rays from Cold Fusion

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This study made a nice case for using *K*-shell x-rays from palladium created by charged-particle fusion products as a means to measure cold-fusion events. Ejection of the 23-keV *K*-shell electron from palladium could be made only by a nuclear (nonchemical) event, and the detection of the resultant x-ray could be used as a signature for the proton branch of the DD reaction. To test this idea, a 15 x 15 x 0.5-mm palladium foil was electrolyzed in a 0.1M LiOD solution in D_2O at 48 mA (~20 mA/cm^2) for 170 hours, and a γ-x-ray detector with a sensitivity well below 20 keV was used to search for any palladium *K*-shell x-rays. Background was measured by counting with a copper attenuator placed between the cell and the x-ray detector. No temperature change was observed during the electrolysis. Low current density, power-supply problems, and an americium-contaminated detector together contributed to the negative results reported. The technique, however, has merit as an indirect measurement of fusion charged particles; it is simple and spectrographic and can easily be corrected for background.

Fourth Plenary Session (D): Calorimetry

Two Fast Mixed-Conductor Systems: Deuterium and Hydrogen in Palladium—Thermal Measurements and Experimental Considerations

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Three major quandaries in the field of cold fusion were discussed: first, whether anything unusual is happening when deuterium is inserted into palladium at very high activity; second, the fact that even in the same laboratory some samples show effects whereas others do not; and third, the question of the mechanism.

Several factors were suggested that might be important: the microstructure of the palladium lattice (cast palladium appears to behave differently than material treated otherwise, and it is well known that dislocations act as traps for hydrogen); interstitial composition (materials are outgassed by remelting 10 to 12 times with an arc in an argon atmosphere that is flushed each time); blocking layers on the surface (no gas is evolved from electrodes whose surfaces have not been properly cleaned, and cell resistance increases suddenly when something is done wrong); carbon interstitials (palladium is often melted in graphite crucibles); hydrogen-deuterium exchange; and preferential absorption of hydrogen over deuterium.

The work involved conventional calorimetric methods and a direct comparison of the deuterium-palladium and hydrogen-palladium systems. No nuclear products were searched for. Electrolytic cells featuring cast Pd buttons 2 mm thick were run, and arc-emission spectroscopy was used to determine the purity of the Pd. Calorimetry was done with dynamic power balancing (by adding heat with a resistor and plotting temperature difference in the bath versus power input, with either the resistor or the cell as a source of power, then comparing the two curves). Initially, the slope of the temperature versus power curve for the cell is less than that for the resistor calibration curve by an amount that roughly accounts for the work done to separate water by electrolysis. After charging, the slope eventually exceeds that produced by the resistor, implying net power production, including the loss for electrolysis. The experiments were carefully kept in the range for which additional stirring had no effect. Also, it was shown tha the exothermic effect of recombination could, at the most, just eliminate the endothermic effect of electrolysis.

Excess heat generation was found in the cell with heavy but not with light water. At early times, both cells exhibit an endothermic effect but eventually, in one experiment, the deuterium cell temperature rose enough to give 12% excess heat above the calibration and 22% excess heat above the hydrogen cell. It was concluded that the excess heat cannot be due to recombination or any other exothermic effect and amounts to no more than 7% of the endothermic effect.

Calorimetric and Thermodynamic Analysis of Palladium-Deuterium Electrochemical Cells

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The unique calorimeter being used at Sandia was still experiencing experimental difficulties and so no results were reported. However, the device measures heat by completely surrounding the electrochemical cells with liquid Freon and using the flow rate from the vaporization of Freon to measure heat. As such, it is not a microcalorimeter and can be used to do experiments on large electrodes with large current densities (it will measure on the order of 40 W of power with a precision of about 0.1 W).

It was emphasized that the heat energy from a calorimeter is not equal to the electrical energy being put into the electrochemical cell. In particular, the voltage of the cell is equivalent to the free energy, whereas a calorimeter measures the enthalpy. The difference between the two is related to the entropy of the reaction inside the cell multiplied by the temperature. Other factors require consideration, such as heat dissipated outside the cell from escaping gases. The speaker emphasized the feeling that the thermoneutral potential term (from calorimetric rather than electrical work measurements) already includes the vaporization of the heavy water to D_2 and O_2 gases. It was further shown that heat from palladium deuteride formation whould be a small but significant quantity (~36 kJ/mole). This would represent about 0.02% of the the 20 W/cm^3 heat reported by Pons, Fleischmann, and Hawkins.

Nuclear and Thermal Effects During Electrolytic Reduction of Deuterium at a Palladium Electrode

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The observation of a burst of heat accompanied by a burst of neutrons during the electrolytic reduction of deuterium was reported. The electrolysis cell had a working electrode of palladium (5 x 6 x 20 mm parallelepiped) with a thermocouple embedded in it, a Pt gauze cylinder for a counter electrode, a Hg/HgO/OD$^-$(0.1M) reference electrode, and a LiOD (0.1M) in D_2O (99.5%) electrolyte solution. The electrode temperature was measured rather than an energy balance, and the system was programmed to switch off the electrolysis when the temperature reached 80°C, which it did during the observed burst. Neutrons with an energy range up to 7 MeV were measured. The ^{3}He dosimetry was calibrated with an Am-Be source and, in the experiment, had an estimated efficiency of 5×10^{-5}.

The burst occurred when no one was in the lab, but it was later estimated that during the 4 minutes of the event 36 neutrons were counted (about 150 times background), the electrode probably reached 150°C, part of the solution evaporated, about 200 J of energy was generated, and, taking into account the efficiency of the neutron detector, about four orders of magnitude more neutrons were seen than would be expected if the excess heat was due to nuclear fusion.

Calorimetric Measurements on Electrochemical Cells with Pd-D and Pd-H Cathodes

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Two types of calorimetric experiments were described. The first was a differential comparison of temperature between identically constructed and operated palladium-hydrogen and palladium-deuterium cells using 6.25-mm diameter and 5-cm long palladium electrodes. The electrolytes were saturated with LiOH and LiOD respectively, to increase conductivity and lower the I^2R heat effect relative to any excess heat generation. Problems with this experiment were exchange with normal water in the air and temperature differences due to different conductivities of the two electrolytes.

The second calorimetric experiment was conducted in a semi-sealed cell using a constant heat-loss rate calorimeter whose precision was 0.1 W total (or 80 mW/cm^3 of the palladium electrode). In the energy calculations, such things as electrolysis, recombination, palladium deuteride formation, heat of evaporation, and water loss were accounted for. No excess heat was observed within the defined boundary conditions despite current densities that ranged from 12 to 500 mA/cm^2 and 1200 experimental hours with 6 cells. The longest experiment had a total charge input of 700 A-h.

Neutron Detection with Low-Level Background

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The construction of a very sensitive neutron detector was reported, based on a scheme essentially the same as that used for neutrino detection. In both cases, interaction of the particle with a proton results in a low-energy neutron that can be captured by ^6Li in a liquid scintillator. Pulse-shape discrimination is used to separate contributions from positrons. The detectors have extremely low background and high neutron-detection efficiencies, yield good neutron energy measurements, have 2.5-ns time accuracies between events (to record bursts), and record all parameters on tape.

Two detectors have already been set up, one in the Frejus tunnel, another at Bugey. Cold fusion experiments could easily be placed in the Frejus detector. A number of experiments, including both electrolysis and pressure experiments, have been run, but no neutrons above background have been detected. The investigators invite anyone with a serious interest in detecting neutrons to use their detector.

Seven Chemical Explanations of the Fleischmann-Pons Effect

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Mechanisms have been examined that could explain the generation of excess heat in a Pons-Fleischmann electrolysis cell. Recombination of hydrogen and oxygen in the gas phase could generate considerable heat but has not been observed in six measurements of recombination by three different groups at Texas A&M. Recombination might also occur when D_2 is released when the electrolyte level drops and uncovers the top of the electrode. Calculations show this contribution to be about 0.27 W/cm^3, and surface films that slow oxygen diffusion could contribute another 0.04 W/cm^3. Experiments show no effect. Bubbles of oxygen hitting the palladium electrode may contribute 0.3 W/cm^3. The alpha-to-beta transition of palladium would contribute negligibly if spread over the typical 100-hour time scale for excess heat generation. Formation of palladium deuteride is calculated to contribute only 0.07 W/cm^3, and formation of a lithium alloy can contribute no more than 0.1 W/cm^3. Collapse of an unstable deuteride, as suggested by Linus Pauling, appears unlikely but, in any case, should contribute no more than 0.9 W/cm^3. The only process that seemed to be a possible explanation is recombination, but this mechanism is not supported experimentally. Although ~10 W/cm^3 are typically reported for successful Pons-Fleischmann experiments, calculations and experiments using chemical explanations could account for no more that 2.1 W/cm^3.

Evidence Against Condensed Matter Fusion Induced by Cosmic-Ray Muons

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Muon-catalyzed fusion would involve: muon capture by the deuterium (even though the Pd-D capture ratio, proportional to Z, is 46); absence of muon transfer from D to Pd (even though prior work indicates a transfer rate of 5×10^{11} per second); and extraordinarily enhanced fusion

rates in the Pd-D system (several hundred fusions compared to the predicted 0.2 fusions per muon). Nevertheless, Nagamine described an experiment to measure such fusion. The muons were produced by a 500-MeV proton accelerator; the targets were (1) a Pd target loaded with deuterium for 10 hours up to the D/Pd ratio of 0.6 and (2) an electrolysis photochemical cell (control samples were Pd without any deuterium). The experiments indicated that the fusion yield was below 0.012 fusions per muon. Using this limit, muon fusion can lead at most to 10^{-6} neutrons per second for cosmic-ray induced deuterium fusion.

Study of Energetic Charged Particles from Thin Palladium Foils Subject to High Current Densities

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A low-energy, high-current particle accelerator was used to implant deuterium ions to high density in micron-thick foils of evaporated palladium. Following the implantation, spectra of charged particles emitted from the foil were measured while the target was subjected to current densities up to 2 A/cm^2, considerably higher than those used in the typical electrolysis experiment. The rationale behind the work is that the heat generated by some sort of two-body nuclear reaction will be manifested as charged particles. However, if the energies of those particles are in the range from a few to 10 MeV, only thin foils can be used to assure the products can be measured before slowing down in the metal.

A surface barrier detector was used not only to look for reactions after the deuterium loading but to monitor the loading process itself. This was done by looking at the count rate for the protons made from the D-D reaction during bombardment. Deuterium-palladium ratios slightly in excess of one were observed, which, surprisingly, remained fairly stable (±20%) for weeks. The stability may have been due to a 0.05 μm coating of silver over the Pd.

With the beam turned off, a broad peak at about 5 MeV was reproducibly observed, which persisted for different currents applied through the foil and over long periods of time. There was also a suggestion of a peak at 3 MeV. The count rate for the 5-MeV peak, corrected for background, was about 30 counts per day at the maximum, and increased linearly with applied current density up to 2 A/cm^2, but dropped off for one data point at 8 A/cm^2. Control experiments with the current off and a nondeuterated target showed nothing above background. Thus, there appears to be a group of charged particles being emitted at 5 MeV that correlates with current and with deuteration.

It was suggested that the broadness of the 5-MeV line might be due to a superposition of separate lines resulting from a D-P reaction with the palladium nucleus. Palladium has various stable isotopes that could participate in an exothermic reaction with deuterium and release a charged particle in the region of 5 MeV. However, to achieve significant reaction rates, one has to invoke a mechanism to reduce the impact of the Coulomb barrier. The Phillips-Oppenheimer polarization effect was mentioned, but this idea received little support from the audience.

Fifth Plenary Session (E): Applicable Condensed Matter Physics, Applicable Electrochemistry, Analytical Chemistry of Appropriate Products

Perturbed Angular Correlations (PAC) Studies of Electrolytically Charged Metal Cathodes

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The use of PAC to measure interaction frequencies and quadrupole interactions to gain insight into the symmetry of local sites was described. Hydrogen trapping in vacancies, the formation of nickel hydrides, and the role of lithium cations were examined using the PAC technique. Possible applications to the hydrogen-palladium system were described, whereby complete disruption through fusion of a hydrogen-vacancy complex might be observable. This conjecture remains to be examined by experiments, which are just beginning. It is unlikely that PAC will be applicable to hydrogen held in a solid at grain boundaries, crack tips, bubbles, or other occlusions.

Interaction of Deuterium with Lattice Defects in Palladium

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A continuing effort was described that uses ion beams and ion implantation to understand the interaction of hydrogen isotopes with defects in metal lattices, such as in palladium. The theory used to understand the experimental data is one in which the host is replaced by an effective medium of jellium, an electron gas. In particular, much about hydrogen-metal interactions can be understood in terms of an embedding energy that depends on the interstitial electron density and on a less significant term that depends on the degree of filling of the d band in the metal.

Experimentally, deuterium was implanted at low temperatures (at energies of ~15 keV), then the crystal was bombarded with 750-keV ^{3}He ions, which allows probing the deuterium

within the first half-micron of the surface. The interaction of the implanted deuterium with both lattice defects and He bubbles/voids in single crystals of Pd were described. The bubbles were found to trap D with a binding enthalpy of 0.31 eV relative to the solution site. Implantation-damage-trapped D, however, had three different binding enthalpies, 0.31, 0.23, and 0.15 eV. These were attributed respectively to vacancy clusters, monovacancies with low D occupancy, and monovacancies with high D occupancy. Each Pd vacancy can accommodate up to 6 D atoms. At low temperature (25 K), D occupies octahedral interstitial sites; at 100 K, D becomes trapped by vacancies; and at 200 K, just before depopulation from the vacancy is initiated, 60% of the D is at near-tetrahedral sites and the remaining 40% is deposited 0.3 Å from the octahedral site and toward the vacancy. Besenbacher commented that he felt the chance of having two deuteron nuclei close together, say in the same octahedral site, was zero.

Search for Cold Fusion in Superstoichiometric Palladium Deuteride Using Ion Implantation

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Techniques were described for ion-implantation of D into Pd at 40 K using high fluences and energies of 10 keV. These techniques yield compositions up to a D:Pd ratio of 1.3. A detector was then used to search for high-energy D and T particles that might result from a D-D nuclear reaction and to monitor the buildup of the D concentration. After the beam was turned off, however, fusion events were not detected during ~9 hours of counting at 40 K. The estimate of the upper bound on the fusion reaction rate is 10^{-21} events/D·s. Similarly negative results were obtained for D-implanted Zr.

Monitoring of the D/Pd ratio during warmup showed that the concentration decreased in two stages. The first stage, at 120 K, was attributed to rapid diffusion of the excess D in the superstoichiometric hydride; the second stage, at 220 K, was ascribed to D release by conventional diffusion in the normal hydride phase.

Tritium Enrichment in the Electrolysis of D_2O

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Deuterium is extracted from water (145 ppm D) by the counterflow of high-pressure H_2S ($HDS + H_2O \rightleftharpoons H_2S + HDO$) in a tall column. Water also has one part in 10^{18} of tritium, which is also enriched by this process. One stage extracts 15% D_2O and 24% of the T in the water. Successive stages further purify the D_2O, and the end product contains ~ 6.5×10^8 T atoms per cm^3 of heavy water. For more efficient stages this number goes down, since less feed water is needed. In the electrolysis of water, tritium, being the heavy isotope, will be enriched. The ratio of the final T/D to initial T/D is the relative enrichment factor, which varies from 1.4–1.6 to 3.1–5.1 (variation due to normal range of concentration ratios k_d/k_t of 1.6–2.2) as the fraction of heavy water electrolyzed varies from 60% to 90%. This would explain increases in T levels after long cell runs. During the question period it was pointed out that T levels in gaseous D_2 can be much higher than in heavy water, and that if cells are purged with D_2 gas, T may build up in that way.

Nuclear Fusion from Crack-Generated Particle Acceleration

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As a conventional explanation of cold fusion, it was proposed that hydrogen loading of palladium produces lattice stress, lattice cracking, and charge imbalance on both sides of the crack. Such a situation creates a capacitor-like increase in voltage that may accelerate deuterons to kilovolt energies, the range of energy needed in ordinary nuclear fusion.

Using an estimation of the RC time constant in the lattice around a crack, cracks of the order of 500 to 1000 μm would allow enough time to accelerate the deuterium atom before the gap discharges. However, the resistivity can be raised by a number of factors, including other cracks, phonon noise, etc. Their calculations showed that if cracks are formed at the rate of tens of square centimeters per second, then watts of electrical power may be released and appear as excess heat.

Search for 0.8-MeV ^{3}He Nuclei Emitted from Pd and Ti Exposed to High Pressure D_2

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This work was stimulated by the high-pressure D_2 Italian work, (DeNinno et al.), and is an attempt to replicate those experiments. A search for the ^{3}He that would be created in the fusion of two deuterons used a plastic detector previously used to detect cosmic rays as well as alpha particles from reactive sources. The detector is highly efficient because almost any alpha particle or ^{3}He that impinges on the plastic will produce a track.

After completing a temperature cycle with Pd that had been pressure-loaded with D_2, no evidence of ^{3}He production was observed (less than 3 tracks/cm^2, which corresponds to a reaction rate about 2 to 3 orders of magnitude less than the results of Scaramuzzi and coworkers). A room-temperature "flexing" experiment to generate cracks also gave a null result. A control experiment with uranium (generating alpha particles) showed the detector worked as expected.

Closing Remarks

Summarizing his impressions at the end of the workshop, co-chairman Norman Hackermann particularly noted the "thoughtful, rational, reasonable, and generally nonirritated discussion" that had prevailed during the sessions. He saw no agreement among the participants that cold fusion was a phenomenon of consequence, however. Hackermann stressed the importance of obtaining reproducible results and of ensuring identical experimental conditions in future experiments. Although he believed that science should ordinarily not be organized, he suggested that in this case it might be desirable for a few laboratories to establish a coordinated effort, which would include free exchange of samples and data, "to try to determine, once and for all, whether this phenomenon is real or not."

Co-chairman J. Robert Schrieffer expressed his belief that the excess heat reported by several investigators was probably real, but that its origin—whether in nuclear or chemical processes—was still very much in doubt. He cited the reports of neutron emission and tritium buildup as indications that fusion was occurring, but said that definitive experimental confirmation was still needed. Schrieffer agreed with Hackermann that reproducibility was a key issue in cold fusion; if the phenomenon can be reproduced, then it will be possible to "deal with the difficult problems rather than only the confusing problems." He compared the present state of cold fusion to the early stages of semiconductor research, and noted that after zone refining and other techniques had evolved, the nature of semiconductors and their unusual behavior became clearer and research could proceed on a firm basis.