Anomalous nuclear effects in solids ("cold fusion"): questions still remain

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The results are discussed of recent experiments to detect the nuclear products of "cold fusion" (neutrons, tritium, and helium) and their possible theoretical interpretation. Apparently low-level neutron emission has been established rather reliably and can be understood without adducing exotic models. The results on tritium and helium require further refinement and as yet have not received a satisfactory theoretical explanation.

1. INTRODUCTION

After a brief period of general interest in "cold fusion" (or "low-temperature fusion"–LTF), (see, e.g., Ref. 1), the belief has become widespread that it is "dead." Such a judgment is usually expressed rather categorically, often even by people who are not directly acquainted with the studies on LTF. This is a "scientific common opinion." At the same time, the materials of recent conferences on LTF[1)] show that the situation here is far from being so evident, and the "death rumors" on LTF apparently are clearly exaggerated, or in any case premature.

The negative attitude toward LTF arose primarily as a reaction to a large number of hasty, unprofessionally performed experiments of the initial period. The scale of interest in LTF reflected the receptivity of our society to scientific ideas and the broad development of means of telecommunications. The extreme simplicity of the LTF experiments (which sharply contrasted with the incredible complexity and cost of thermonuclear studies) stimulated the rapid attraction of specialists in different fields and opened up the possibility of participation in the studies of small groups and even lone amateurs who possessed only the simplest physical and chemical equipment. The result was: lobbying, haste, and a very inhomogeneous composition of the participants in this "race for cold fusion," far from all of whom possessed the necessary preparation and sense of responsibility. A "noise effect," unprecedented in scale, arose, from which it was very difficult to distinguish the "useful signal" contained in the quality experiments. This was the case in which "quantity did not transform into quality," since most of the studies turned out to be unsubstantiated, independently of whether the authors had drawn an affirmative or negative conclusion.

Another factor involves the difficulty of reproducing the results of the experiments, which was "taken by the majority as evidence of the poor quality of the experiments, rather than of a property of the phenomenon under the conditions under which it was studied. Here it is generally recognized that all that is irreproducible and unrepeatable contradicts the spirit of science."[2] Actually the experiments on LTF have proved to be nontrivial in the highest degree, while the signals are sporadic and close to the background level. Although many of the groups obtained positive results in individual measurements, it was not possible to reveal conditions and parameters that control obtaining them.

All this led to the situation that the broad community ceased to believe in LTF and lost interest in it. Deprived of the incentive of immediate practical application, the pursuit of LTF acquired a considerably more tranquil and business-like character, more appropriate to scientific studies. But under this outer cloak of tranquility, the passions continue to boil, which from time to time spill out onto the pages of the press. Here are just a few recent statements of the opponents and advocates of LTF, which give a picture of the character of the polemic (cited in Ref. 3).

Dr. Robert Park, executive director of the American Physical Society, in the newspaper *Washington Post*, 15 May 1991, said: "... The story with cold fusion was determined not so much by faulty science, as by such common human failings as greed, ambition, and vanity... There is no doubt that among the searchers for cold fusion there are true believers, just as there are sincere scientists who believe in psychokinesis, flying saucers, creation of the world, etc. A scientific degree still does not vaccinate one against obtuseness and lying."

Dr. Roland Parker, head of the Center for Plasma Fusion of the Massachusetts Institute of Technology, in an interview in the newspaper *Boston Herald*, said: "...Now the question is no longer whether they (the original discoverers of LTF Fleischmann and Pons) interpreted their experiment incorrectly.., as much as whether this might have been a deliberate fraud."

Admiral James Watkins, head of the Department of Energy of the United States, in speaking on 6 May 1991 to the Association of American Newspaper Publishers, said: "Remember cold fusion? News on the front pages... . What is this–key to our energy freedom or an inflated mystification? Ultimately it has proved to be neither the one or the other. Just bad science... . However, considerable damage was done here. Owing to these two members of the scientific society, every person clothed in a white labcoat looks like a swindler... ."

We should acknowledge that there are more than enough grounds for such a severe critique. Here there are both many experimental studies in which the accuracy of the

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measurements and the reliability of the apparatus were exaggerated, and theoretical models that contradict well established laws of nature and do not stand up to elementary verification. Naturally, all this causes exasperation.

No less categorical in their pronouncements are the extreme enthusiasts of LTF. As a rule, they are inclined to acknowledge as fully reliable all the experimental results, while they view the criticism as the consequence of a "plot of the scientific Mafia," which protects the billions granted for studies on traditional thermonuclear fusion. Here are only some samples.

Carol White in the article "The Cold Fusion Revolution" in the journal 21st Century said: "Cold fusion perhaps is the most important discovery of this half of our century, and the conference (at Como) confirmed this.... Two hundred men and women present at the conference expressed the resolve to fight for the truth as they see it, independently of the cost in their material status or reputation. They rejected capitulation before the tyranny of organizations such as the American Physical Society, journals like "Nature," or lying journalists who write for the popular press."

Professor Robert Bush of the California State Polytechnic University said: "The conference was a signal of success.... The general opinion was that research on cold fusion not only has not ceased, but is continuing and growing stronger."

Doctor Heinz Gerisher, recently the director of the Max Planck Institute, in speaking of the statements on the predominance of tritium over neutrons in LTF experiments, said: "If these quantities are correct, if the revolution in nuclear theory must combine solid-state theory with nuclear forces, we have a fantastic new discovery." (One cannot help but agree with this; however, the problem lies just here–are the experimental data true!) At times the polemics recalls the religious wars, when above all a triumph of faith is important, rather than elucidation of the truth. Moreover, one should not be especially amazed at this. In a situation when a reliable observational basis is lacking, many judgments on LTF are based on intuition rather than facts. Such a situation is quite characteristic of the initial period of studies of a new phenomenon, and early or late, it is resolved by confirmation or rejection of the reality of this phenomenon. One can give many examples. To recall also, the kind of objects, sometimes highly exotic, that are introduced, for example, in elementary particle physics: "taxions," "maximons," "wimps," "champs," "Centaurs," etc. In time some of the hypotheses are confirmed experimentally. Outstanding recent examples are quarks and intermediate bosons. Most of the other hypotheses are rejected. This is the normal course of research. Yet if one tries to classify the different approaches on the basis of far-fetched philosophical concepts,[4] then one can easily assign to the "pathological" category many fields of modern science, since errors and doubts are unavoidable in studying a new field. Hasty and categorically negative judgments are just as dangerous as positive judgments. A classic example is the estimate of the prospects of the Lagrange–Hamilton method in elementary-particle theory given at the conference at Kiev in 1959 by the eminent Soviet theoretician L. D. Landau, who stated that the Lagrangian "is dead and must be buried with all due honors." Several years passed, and outstanding success in elementary-particle theory was attained precisely on the basis of the Lagrangian method.

The research on LTF still exists at the stage when it is premature to draw final conclusions. It is more reasonable to turn to the experimental data obtained recently, and try to evaluate their degree of reliability and see what they teach us.

In the three years that have passed since the first reports on LTF, the experimental technique used in these studies has been considerably refined. The efficiency of the detectors has been increased: (from 10^{-5} in the first experiments to 30–45% in the later ones), and their reliability and noise shielding have been improved.

The observations that are adduced as evidence in favor of LTF can be classified into three groups:

a) *Data on "direct" detection of the products of the nuclear reactions of* dd*-fusion.* Mainly they are neutrons from the reaction

$$d + d \rightarrow n + {}^3He \qquad (1)$$

(The data on charged particles are more meager and contradictory.) The method has the greatest sensitivity and allows one to detect events at the level of 10^{-2}–$10^{-3} s^{-1}$ (the so-called "Jones level"), which corresponds to the rate of the reaction

$$\Lambda \sim 10^{-22\pm1}\ s^{-1}\ (dd)^{-1}.$$

b) *Results of radiochemical and mass-spectrometric measurements of the content of tritium and helium from the reactions*

$$d + d \rightarrow p + T, \qquad (2)$$

$$d + d \rightarrow {}^4He + \gamma \qquad (3)$$

in specimens or gases. The sensitivity of this method is many orders of magnitude lower ($\sim 10^{-9}$) than that of the neutron method. Advantages are the relative simplicity and possibility of accumulating T (or ^{4}He) in a long experiment. The most striking result reported by certain groups is the predominance of T (and ^{4}He) over neutrons, in contrast to the expected ratio $T/n \approx 1$.

c) *Signs of excess heat release* ΔQ (as compared with the energy Q spent in saturating the specimens with deuterium). This method is the least sensitive. If the known nuclear reactions of *dd*-fusion (1)–(3) are responsible for the heat, then an excess energy release at the level of 1 W corresponds to 2×10^{12} and 2.7×10^{11} reactions per second by the channels (1), (2) and (3), respectively. If the heat release is large and exceeds all the known sources of energy release of nonnuclear nature, this method of detecting LTF is the most direct and simple.

The status of the observations a), b), and c) differs. The sharpest disagreement is associated with the measurements of excess heat release. Several groups continue to report positive results on $\Delta Q/Q$ that attain from several percent to thousands of percent. If these results were true; then evidently we would be dealing with a completely new physics and prospects of energy-generation applications. However, it is precisely these results that arouse the greatest doubts and objections. Since up to now they have not gone through a broad testing, it seems reasonable to await new, more unam-

biguous data. Therefore we shall not discuss here the calorimetric experiments.

The observation of neutron emission, even at the very low "Jones level" is certainly very interesting and unexpected. It exceeds by about 40 orders of magnitude the rate of fusion of deuterium in the "natural" state–in the D_2 molecule. However, as will be shown below in Sec. 5, such a rate, albeit requiring the realization of highly nontrivial conditions, still apparently can be understood on the basis of known concepts of nuclear physics and solid-state physics.[1] Practical applications here as yet are not in view. Moreover, even at such a low rate, the phenomenon might have important consequences for global geophysical and cosmological scales. On the whole the possibility of LTF at this level does not arouse special objections.

The situation differs with the statements on the predominance of formation in LTF of tritium ($T/n \sim 10^9$) or ^{4}He. Although in this case energy generation is still not evident, other practical applications (e.g., preparation of T are quite possible. At the same time, the breakdown of the relationship $T/n \approx 1$ would be unconditionally a signal of new physical phenomena. This also pertains to the predominance of the channel yielding ^{4}He, which in the free state (reaction (3)) is suppressed as compared with channels (1) and (2) by several orders of magnitude.

The aim of this review is to discuss the results of the experiments performed recently on detection of the nuclear products, n, T, and ^{4}He, which are poorly known to broad scientific circles. Extensive new data on detection of neutrons were presented at the conferences and symposia held in 1991. There is no possibility nor even need to present them all. We shall restrict the discussion only to several selected studies that possess, as we see it, high reliability and plausibility. We shall also examine the recent studies on detection of tritium and helium.

The final section will briefly summarize the results of analyzing some popular theoretical models of LTF.

2. NEUTRON MEASUREMENTS

Despite the known difficulties of detecting neutrons, this method of detecting LTF enables the greatest sensitivity, owing to the high penetrating power of neutrons. The highly efficient neutron detectors invented in recent years enable one under conditions of low-background experiments to detect the emission of neutrons at the level of several events per day.

The features of neutron measurements in LTF have been analyzed in Ref. 5. The key parameters of neutron detectors are: efficiency, energy resolution, time-dependent information, sensitivity to the γ-ray and cosmic-ray backgrounds, and sensitivity to noise.

The fundamental methods of detecting the 2.45-MeV neutrons expected from dd-fusion are: detection of fast neutrons by recoil protons, thermalization with subsequent detection of the slow neutrons, and a combination of these methods (the "fast-slow" variant).

The advantages of detecting fast neutrons are: the possibility of measuring the energy of the neutrons, fast time-dependent information, and a lower neutron background (most of the background neutrons are slow). The advantages of detecting slow neutrons are: high efficiency, simplicity of handling low sensitivity to the γ-ray background, and the ability to detect "bursts."

The fast-slow variant enables one to suppress the background most effectively.

Tables I–III[5] present the main features of the different types of detectors, possible sources of interference, and means of shielding from noise.

Now let us examine the results of some recent studies performed by using various techniques and possessing high reliability.

2.1. Experiments of the group of K. Wolf (University of Texas) on detection of fast neutrons in the electrolysis of D_2O[6]

The detector (Fig. 1) is based on a liquid scintillator (NE 213) equipped with a photomultiplier. The energy resolution is not very high, but it enables one to single out the interesting region of energies and thus diminish the background. The sensitivity to γ-ray quanta is suppressed by pulse-shape analysis, so that the γ-ray background amounts to less than 10% of the total background. The cosmic-ray background is suppressed by anticoincidence shielding (a plastic scintillator fitted with a photomultiplier) and a layer of paraffin (25 cm). The neutron component of the cosmic rays constitutes the main background.

The first experiments used two identical detectors, and the later one four.

The average background amounted to 0.5–0.8 events/min. An appreciable variation of the background was observed with a period of about 1 h, which approximately doubled the magnitude of the standard deviation. Simultaneous

TABLE I. Neutron detectors used in LTF research.[5]

Type	Energy of neutrons	Reaction	Typical efficiency,%	Sensitivity to γ-quanta
^{3}He counters	Thermal	^{3}He(n,p)	1–44	No
BF_3 counters	"	^{10}B(n,α)	0.5–20	No
H_2O + NaI/Ge	"	H(n,γ)	0.1	No
Activated foils	"	(n,γ) or (n,F)	0.1–5	No
Li glass	"	^{6}Li(n,α)	1–20	No
Liquid scintillators	Fast	n,p-recoil	1–25	Yes
Plastic scintillators	Fast	n,p-recoil	1–20	Yes
Combination	Fast/thermal	(n,p) + (n,α)	10–25	Yes/No
Cherenkov detectors	Thermal	(n,γ) + e	15–20	High energy

TABLE II. Potential sources of false signals.[5]

a) Electrical interference
1. Leakage of high voltage (moisture sealing)
2. Electromagnetic induction (shielding)
3. Interference in power lines (filters, veto counters)
4. Microphonic effect
b) Cosmic-ray background
1. Total counting (interaction of cosmic rays in the shielding)
2. Coincidence counting (bursts in the detector and shielding)
3. Reactions in D_2 in the target
c) Laboratory neutron background
1. Accelerators and reactors
2. Radioactive sources
3. Natural radioactivity (uranium, radon)

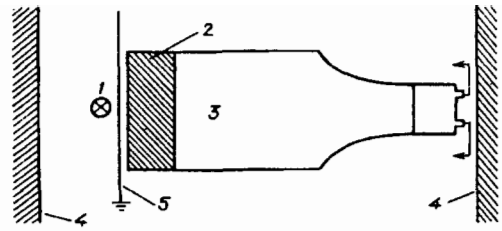

FIG. 1. Neutron counter.[6] *1*–cell, *2*–NE 213 liquid scintillator, *3*–photomultiplier, *4*–paraffin, *5*–steel plate.

monitoring of the background with an equivalent detector lying at a distance of 30 cm from the main detector (and separated with 5 cm of paraffin) enabled decreasing the background. For control the places of the working and background detectors were periodically switched. To estimate the possible background from radioactivity ($\alpha \rightarrow$n reactions in the cell), the materials used in the apparatus were studied before and after the experiment by using silicon and germanium detectors.

The results of the series of experiments with a large number of cells are summarized in Table IV. Only in a small fraction of the cells ($\approx 1/40$) were positive results found, which we shall discuss below.

a) an experiment with simultaneous electrolysis of D_2O + LiOD in five cells with Pd electrodes (diameter 6 mm, $l = 2$ cm). Preliminarily these electrodes were employed in several cycles of electrolysis for 1–2 days, whereafter their surfaces were cleaned. Approximately 10 h after starting electrolysis (cycle 1), a signal was detected that exceeded the background fourfold and lasted 8–10 h (Fig. 2a).

The procedure of cleaning and saturation, which was repeated after 2 days, yielded no positive result (cycle 2).

After 5 days of charging at 20 mA/cm^2 and cleaning the surface, cycle 3 was started. After 5 h of electrolysis an effect was detected that lasted 4–6 h (Fig. 2b).

Further, electrolysis was performed over 7 days at a current of 20 mA/cm^2, which was then raised to 30 mA/cm^2. At 3.5 h after raising the current, a signal was detected that exceeded the background fourfold and lasted 3 h. This cycle is shown in Fig. 2c and 2d for two energy ranges.

The activity in cycle 9 is shown in Fig. 2e. On the whole, in the experiments of the group, one working detector recorded eight periods of activity at a level 3–5 times higher than the background, while with two working detectors four periods were recorded (cycle 8 is shown in Figs. 2f and 2g).

b) Experiment on simultaneous electrolysis in four cells with a set of Pd rods of diameter 6 mm and total length 25 cm. An electrolyte of D_2O + 5M NaOD was initially used in this experiment. Electrolysis over three months did not lead to a statistically significant excess of the signal over the background. Then the electrodes were cleaned, annealed in vacuo, and electrolytically saturated with deuterium in D_2O + 0.1M LiOD. Nine hours after the onset of saturation a relatively large signal was detected (Fig. 3a), which contained about 1100 counts per hour, which corresponds to a source strength of about 400 neutrons per minute.

Subsequently an excess activity was also observed in the course of several days (Fig. 3b).

2.2. Experiments on detection of slow neutrons by the group of the Los Alamos National Laboratory[5] and the Joint Institute of Nuclear Research[7]

2.2.1.

Over the past two years the Los Alamos group has performed experiments on LTF involving saturation of titanium with deuterium from the gas phase and thermocycling. In this time four detecting systems were built on the basis of helium proportional counters with efficiencies from 20% to 45%, which were used simultaneously in the last experiments. Figure 4 shows a schematic diagram of one of these systems. A detailed study and elimination of sources of false signals was conducted: the shielding from electromagnetic interference was improved, the shielding from false pulses arising from discharges upon accumulation of moisture was

TABLE III. Shielding against false signals.

1. Shielding from electromagnetic induction of signal transmission lines and high-voltage lines
2. Sealing of high-voltage components
3. Filters in power lines
4. Multiple independent segmentation of detectors
5. Two (or more) different detectors
6. Energy spectrum of neutrons
7. Pulse arrival time (delay)
8. External "veto" detectors
9. Variation of distance to detectors
10. Pulse-form analysis
11. Shielding from cosmic rays (underground laboratories)
12. Painstaking control experiments

TABLE IV. Neutron experiments of the group at Texas A&M University.

Type of cells	Number of cells	Results
1. Pd–Pt (Ni), electrolysis	20	No signal detected
2. Pd–Ti, electrolysis	130 analyses for T	< 10 neutrons/min
3. Ti–D_2 gas	9	< 25 neutrons/min
4. Spark discharge in D_2	2	< 150 neutrons/min
5. Ti, D_2 gas, high-frequency induction	4	< 150 neutrons/min
6. 10 cm × 6 mm, Pd–Ni LiOD, electrolysis	3	20–50 neutrons/min
7. 25 cm × 6 mm, Pd–Ni		
NaOD, electrolysis		< 16 neutrons/min
LiOD, electrolysis		400 neutrons/min
8. Stimulation by n, e, γ, α		< 10 neutrons/min
9. 5 cm × 5 cm × 0.25 cm Pd–Ni, LiOD, electrolysis		< 10 neutrons/min
10. Pd (Ti alloy)-Ni, LiOD	4 cells	< 10 neutrons/min
11. Pd (Ce alloy)-Ni, LiOD	4 cells	< 10 neutrons/min

improved, while part of the experiments was performed in a low-background underground tunnel and shaft with use of low-background ^{3}He counters. The neutron background in coincidences for different arrangements of the detectors amounted to from two events per hour to 0.5 event per week (Fig. 5).

Now we shall discuss only the results of the last series of experiments presented at the conference at Como. To study the possibility of "activation" of the titanium specimens, various regimes of saturation and thermocycling were used. Out of 19 tested variants, an appreciable activity could be attained only in the following two experiments:

a) Ti (304 g), degassed at 230 °C and flushed with ^{4}He, was placed in a stainless-steel tank of volume 1 L. After sev-

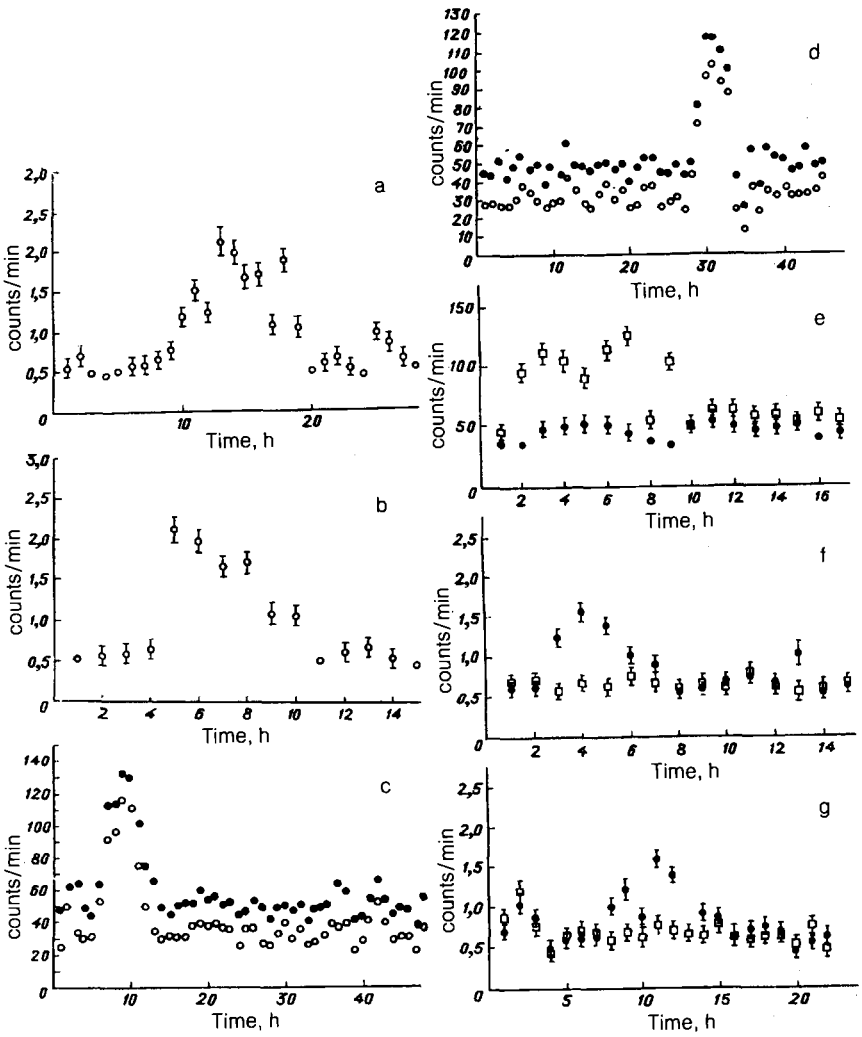

FIG. 2. Results of measurement of neutron emission[6] (a–g). First series: c—17 Mar. 1990; d—30 Mar. 1990, open dots—2.6 MeV, solid dots–1–5.5 MeV; e—f: dots: system 1, squares—system 2; g—after 8 days of electrolysis, 19 May 1990.

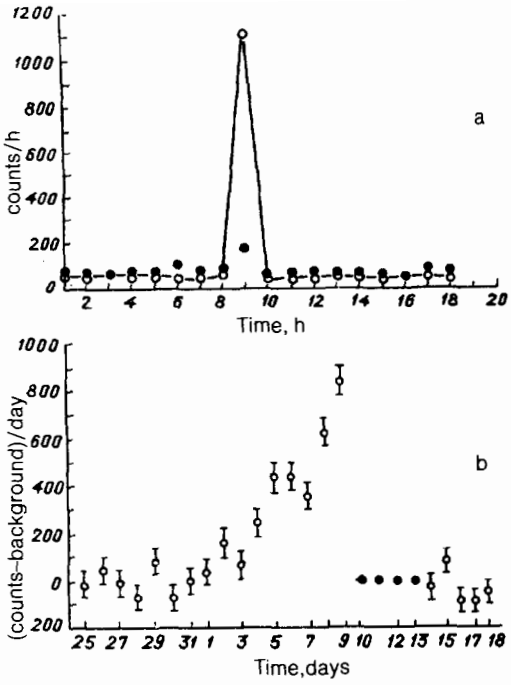

FIG. 3. Results of measurement of neutron emission.[6] Second series: crossed circles—electrolysis was not performed.

en thermal cycles with cooling in liquid nitrogen and subsequent heating to room temperature, a rapid (in 15 s) exothermic absorption of deuterium occurred. After this the specimen was cooled in liquid nitrogen over 10 min and then was warmed. During the first 2 h after this the specimen emitted the three bursts of neutrons shown in Fig. 6a,b.

After three additional thermal cycles with a small level of emission, the specimen was placed in another detector having great sensitivity, located in the tunnel (at 70-m depth). In the first thermal cycle the specimen emitted a large burst of neutrons (Fig. 6b,c), and then two more. An excess of neutrons was observed for about 50 h more, during which time 15 bursts were registered. In addition to the "large" bursts, an excess of "small" time-correlated events was detected, in which two neutrons were detected within an interval of 128 μs. The background of correlated events in this counter having a control cell amounted to 2 events/day.

b) A specimen of 56 g Ti in the form of titanium sponge and trimmings of plates, on one side of which a thin layer of

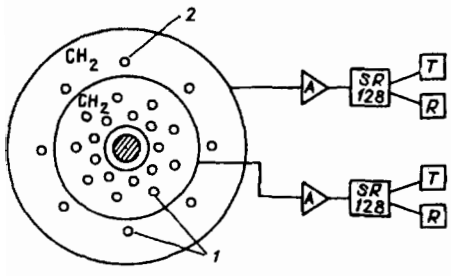

FIG. 4. Detector based on ^{3}He counters. *1*—^{3}He counters, *2*—outer ring, *A*—amplifier, *SR*—accumulator, *T*—counting circuit for total count, *R*—coincidence counting circuit. The counters of the inner and outer rings have independent electronics, and the ratio of the signals in these counters is used for independent control.

Pd had been deposited, was placed in a tank of volume 250 mL. Previously this Ti had been saturated with deuterium by electrolysis of D_2O.

After heating to 220 °C in vacuo the Ti was saturated with D_2 at a pressure of 53 atm. After 90 days of the experiment, the pressure in the tank had declined to 43 atm.

Figure 7 shows the results of the control measurements with a 300-mL tank containing 100 g titanium chips and air, and of the working measurements. We see that over several days an excess of neutrons was observed, which reached 1.12 events/h.

2.2.2.

The Dubna group used detectors of the same construction as the Los Alamos group, but based on BF_3 counters. The inner ring contained 16 counters, while the outer ring contained from 17 to 22 in different configurations, with an overall efficiency from 20 to 26%. Specimens were used of Ti that had been saturated with deuterium, both electrolytically and from the gas phase. We note the following distinguishing features of the experiments of this group.

a) The structure of the electronics enabled obtaining both amplitude and time-dependent information on the detected signals, which substantially diminished the background and increased the reliability of the selection of "useful" events.

All events were recorded that arrived during 1 ms after the first pulse. Here the amplitudes of the first two pulses (corresponding to capture of thermal neutrons in the boron counter: $n + {}^{10}B \rightarrow \alpha + {}^{7}Li$ were analyzed and compared with the given threshold. The time of arrival was recorded for the rest of the pulses.

The method of data processing was based on analyzing the distribution of time intervals between successive events inside the 1-ms "window;" it enabled distinguishing the correlated events of burst type.

The experiment with saturation from the gas used 40 g of chips of a titanium alloy (86% Ti + 6% Al + 6% V + 2% Sn) placed in a stainless-steel cylinder (diameter 28 mm, $l = 1000$ mm). Before the measurements the material was subjected to a procedure of vacuum-thermal aging and saturation with deuterium analogous to that which was used by the Los Alamos group. Then the specimen, cooled to liquid-nitrogen temperature, was placed in the detector; neutron emission was measured as it warmed to room temperature. After 14 h, the target was removed from the detector and placed in a Dewar vessel containing liquid nitrogen, while a control cell without D_2 was set in its place for background measurements. Eleven such cycles were performed in all. Moreover, seven series using "cryoshock" were performed–heating of the specimen to 1000 K and then fast cooling in liquid nitrogen, after which neutrons were detected for two hours.

In the experiment with electrolysis of $D_2O + 0.1$ M LiOD, two types of titanium cathodes were used–without a coating and with a thin coating (0.4 μm) of a nickel film. The latter hinders the formation of an oxide film and facilitates the fast penetration of deuterium into the titanium specimen. The total time of the experiment was 160 h at a current of 120–170 mA/cm^2. The background measurements were performed with H_2O and a "fresh" cathode.

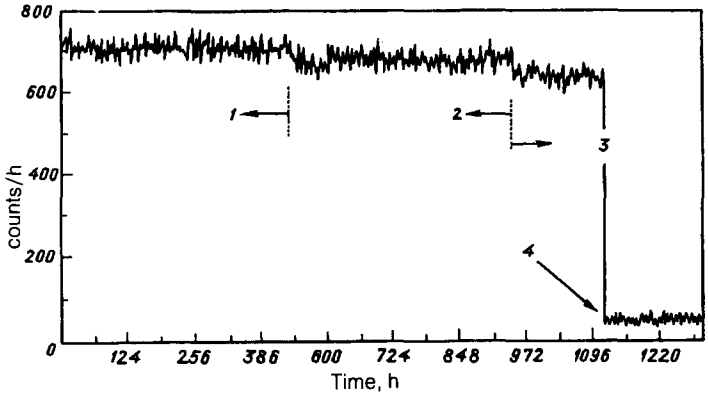

FIG. 5. Background in the chamber (*1*), for two positions in the tunnel (*2* and *3*), and with use of low-background counters (*4*).

The results of the electrolysis experiments (using Ti with a Ni coating) and the gas experiments were similar. In both experiments an excess emission of neutrons was detected in the form of bursts that arose at the mean rate of one to two per hour. The intensity of the neutron emission in the burst amounted to $(3- - 3.5)\times 10^4\,s^{-1}$, and the mean duration of a burst was 300 μs. We should emphasize that, when Ti cathodes without an Ni coating were used, no statistically significant excess of the signal over background was recorded.

2.3. Experiments to detect fast and slow neutrons

The "fast-slow" variant of detecting neutrons was used in experiments on LTF by the group of S. Jones of Brigham Young University and then by the groups of the P. A. Lebedev–Luganskiĭ Machine Construction Institute and Osaka University. The results of these studies are presented in the reviews of Refs. 1 and 8, and we shall not take them up here.

2.4. The American-Japanese experiment with the Kamiokande underground Cherenkov detector

The group of S. Jones of Brigham Young University reported at the conference at Half Moon Bay[9] the preliminary results of experiments performed jointly with Japanese physicists at the underground neutrino detector in the Kamioka mine. The experiment is interesting in that it used one of the major contemporary installations operating in the field of elementary-particle physics. The extremely favor-

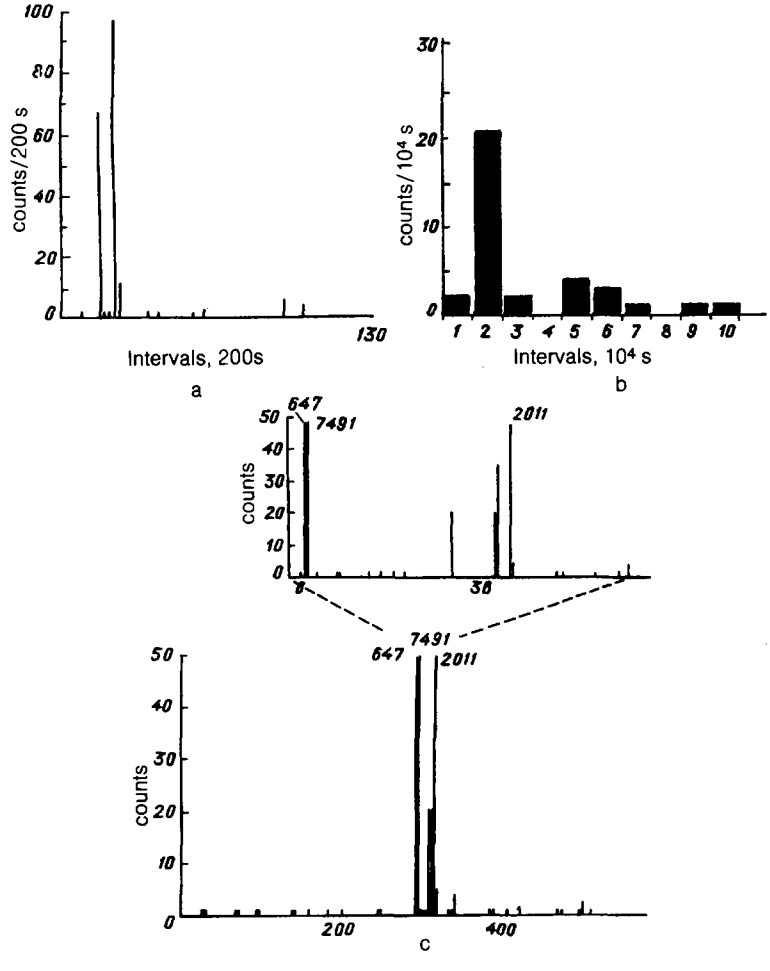

FIG. 6. Results on correlated neutron signals. a—Interval for the inner ring of 200 s. b—The same for the outer ring of 10^4 s. c—Interval of 100 s.

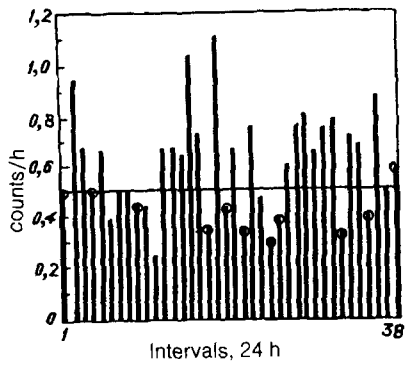

FIG. 7. Counting of correlated neutrons. Each interval = 24 h. Dots–control measurements. Mean background 0.50 counts/h.

able background conditions and the good detection efficiency enable one to obtain data of high reliability. The detector contains about 4500 T of purified water and is fitted with about a thousand photomultipliers recording Cherenkov light. In the experiment being discussed it is emitted by electrons and positrons formed by γ-quanta. The latter are emitted upon capture of neutrons (presumably from LTF) by chlorine nuclei: $n + {}^{37}Cl \rightarrow \gamma + ...$, in a special volume surrounding the cell and filled with a salt solution. The background signals were monitored in an external water volume surrounding the central working volume. In this central part of the detector of diameter 2 m, the background light amounts to about 0.25 counts/h. The efficiency of detection of neutrons emerging from the cell amounts to 20%.

Figure 8 shows the distribution of reconstructed vertices for burst-type events that arise in the process of operation of the electrolytic cell (signals were detected within time intervals of 500 μs). The study of specimens saturated with both deuterium and hydrogen lasting overall over the course of 3450 h showed that the probability of imitation of events owing to decay of uranium nuclei existing in the form of impurities in the Pd, Ti, and other materials of the cell is very small and amounts to $\lesssim 2 \times 10^{-4}$.

A separate experiment measured the neutron emission arising upon solidification of concrete prepared using heavy water. A high statistical significance of the effect was obtained.

Figure 9 shows the distribution of reconstructed vertices from single neutron events for the experiment with D_2O concrete compared with the results of the measurements with H_2O concrete. We see that only in the case of using heavy-water concrete was neutron emission detected in the central part of the detector. Figure 10 shows the distribution of the number of "actuated" photomultipliers, which agrees well with the analogous distribution obtained in calibration measurements with a ^{253}Cf radioactive source.

Neutron emission was detected in all three of the specimens used of D_2O concrete as it hardened (Table V). In contrast, no emission was detected in specimens of H_2O concrete, nor in concrete into which the air of the mine was pumped in the process of preparation, after which the concrete was kept for 6 months. These results mean that long-lived isotopes as a possible source of false signals are apparently ruled out. A number of additional experiments also ruled out possible effects of radon decay. Measurements were performed of the α-activity of the concrete mixture, which could generate neutrons in d(α,n) p-reactions. It was found that it is at least 100 times lower than that necessary to explain the effect. It was proposed to perform another series of additional control experiments.

3. TRITIUM

Up to now a number of sensitive methods of detecting the presence of tritium in various media have been developed that have been used in the LTF experiments. Tables VI and VII[10] compare the fundamental features of the different methods applied for gas and liquid specimens.

To detect tritium in solids, depending on the required sensitivity, dimensions of specimen, and possibility (or impossibility) of destroying it, various methods can also be used.[10] In particular, in the case of powders, good results can be obtained by preparing a suspension in scintillating gels. The greatest sensitivity in measurements with small specimens without destroying them is offered by using flow-through gas proportional counters. Avalanche semiconductor detectors, photographic films, and measurement of β-stimulated x-radiation have less sensitivity.

3.1. Experiments of the group at the Los Alamos National Laboratory on detecting tritium in a Pd–Si–D_2 cell[10]

The experiments of this group employed an original method of initiating an LTF reaction, based on passing a pulsating electric current through an alternating system of

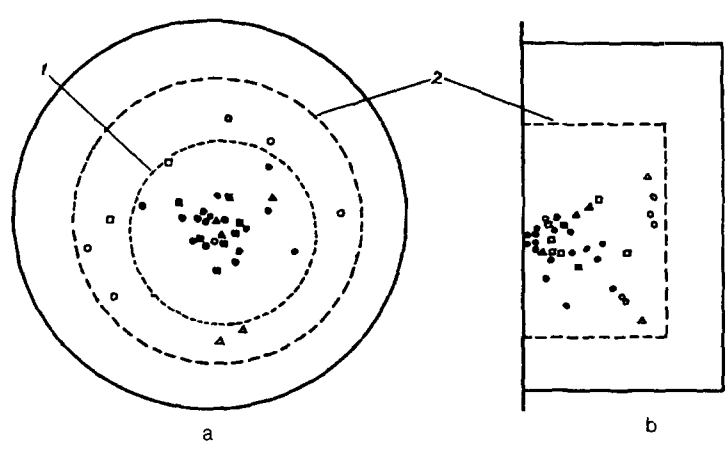

FIG. 8. Reconstructed vertices of neutron events in the Kamiokande detector.[9] a—Top view. b—Side view. Dots–session in Apr. 1991, 457 h: solid dots–signal, open dots–background. Triangles—session in July 1991, 517 h: solid triangles–signal, open triangles—background. *1*—working volume of radius 3.5 m, *2*—volume of 680 m^3.

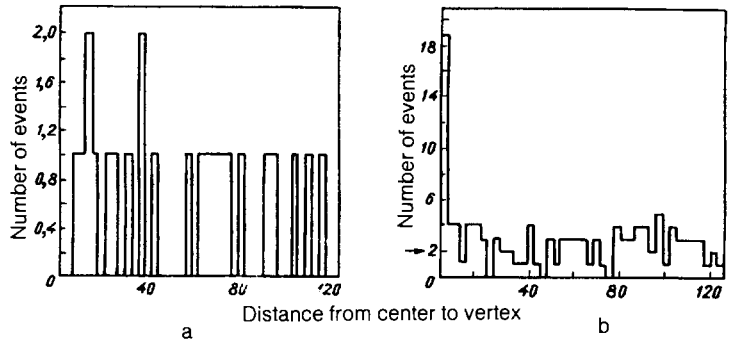

FIG. 9. Distribution of vertices in the Kamiokande detector.[9] a—H_2O concrete, 26.4 h. b—D_2O concrete, 44.5 h.

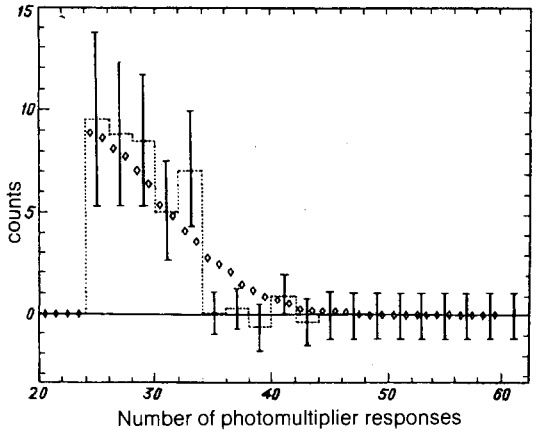

FIG. 10. Distribution of the number of photomultipliers that have responded after subtracting the background.[9] Diamonds–result of calibration with ^{235}Cf.

TABLE V. Emission of neutrons detected in the Kamiokande detector upon solidification of D_2O and H_2O cements.[9]

Series	Duration, h	Counting rate after subtracting background, 10^4 s^{-1}	Specimen
1	41.95	7.2 ± 2.2	790 g D_2O concrete
2	4.46	-0.67 ± 4.6	800 g H_2O concrete
3	39.11	0.64 ± 1.1	790 g D_2O concrete after 6 months
4	44.51	5.8 ± 1.7	1210 g D_2O concrete
5	26.34	-0.67 ± 0.88	1300 g H_2O concrete
6	47.18	-0.47 ± 0.85	D_2O concrete, air from mine
7	65.97	6.3 ± 1.4	760 g D_2O concrete
8	45.55	7.0 ± 1.7	760 g D_2O concrete

TABLE VI. Comparison of different methods of detecting tritium in gases[10] (1 Ci = 3.7×10^{10} disintegrations/s).

Minimum detectable concentration	Method	Time	Volume of gas specimen, cm^3	Discrimination	Widespread application
5 pCi	Condensation, siccative, liquid scintillation counter	1 h	1300	Yes	Yes
10 pCi	Proportional counter filled with the gas being studied	1 min	300	Yes	Yes
100 pCi	Ionization chamber	1 min	2000	No	Yes
1 nCi	Plastic scintillation counter	1 min	20	Yes	No
10 nCi	Photofilm	1 day	...	No	No
100 nCi	Avalanche diode detector	1 min	0.02	Yes	No

TABLE VII. Comparison of different methods of detecting tritium in liquids.[10]

Minimum detectable concentration	Method	Time	Volume of specimen, cm^3	Discrimination	Widespread application
1 fCi/cm^3	Accumulation of ^3He. mass spectrometry	1 mo	10	Yes	No
10 fCi/cm^3	Liquid scintillation counter, enrichment	1 min	100	Yes	No
1 pCi/cm^3	Liquid scintillation counter	1 min	1	Yes	No
5 pCi/cm^3	Plastic scintillation counter	1 min	20	Yes	No
10 pCi/cm^3	Proportional counter, avalanche diode	1 min	···	Yes	No
1 nCi/cm^3	Photofilm	1 day	···	No	Yes

Pd and Si layers placed in a deuterium atmosphere. The early results of the measurements have already been discussed in Ref. 8. In new experiments the sensitivity was considerably improved by using deuterium having a low content of tritium (the background level of T in the D_2 was decreased 300-fold). Moreover, cells with "waffles" of Pd foil were made with a high uniformity of electric characteristics, which enabled gaining good reproducibility of the results and distinguishing the conditions favorable for LTF.

A typical cell (Fig. 11) contained from 12 to 21 g Pd in eight layers (1–2 g per layer) and 6–8 g Si distributed in seven layers 0.76–2.15 mm thick and of diameter 3.17 cm. The Pd was pressed from powder in the form of a disk and then oxidized in air at a temperature of 350 °C for two hours. Palladium foil was also used. Alternating layers of Pd and Si were pressed in the form of a ceramic. The possible impurities were carefully controlled. The deuterium had a very low content of tritium (0.15 $\mu Ci/m^3$; 1 Ci = 3.7×10^{10} disintegrations/s) and 99.995% purity. The palladium powder was obtained by precipitation from an aqueous solution of $Pd(NH_3)_4Cl_2$ and had a particle dimension of 0.3–0.5 μm, forming agglomerates 30 μm in diameter. In all, 512.7 g of Pd powder was used in the experiment, of which 87.3 g was used in various control measurements, as well as 43.2 g Pd foil. The silicon powder had dimensions of 10–20 μm and was bound together with polyvinyl acetate cement, which was also tested for tritium content.

After oxidizing the D_2, the measurements for T were performed with an ionization counter. Owing to absorption of T on the walls of the analyzing system, the minimum background amounted to 3–4 $\mu Ci/m^3$. This "memory effect" is typical of apparatus used in lengthy tritium measurements. The content of T was determined in the original D_2, in the D_2 after filling the cell, and in the D_2 after performing a series of electropulsations and dehydridizations of the Pd.

The overall results of the measurements are shown in Fig. 12. We see that the cells are classified into several groups of differing efficiencies. The yield of T inside each group proves to be proportional to the current. The cells made with Pd foil show the greatest reproducibility, having practically identical electric characteristics from cell to cell. The greatest rate of generation of T was obtained in the cells containing a pressed powder of Pd and Si at voltages above 800 V and current $\approx$0.1 A. Interestingly, in the four control cells containing hydrogen, a small excess of T was also detected, which amounted on the whole to from 6 to 12 nCi. The authors ascribe this effect to displacement by hydrogen of small amounts of TDO from the ionization chamber and from the walls of the gas system.

Although the excess of tritium was small in most of the cells, in one of the cells it proved to be 540-fold larger than the maximum amount of T found upon dissolving the specimens, and 2.2-fold larger than the total amount of T contained in all the deuterium used to fill the cells. The greatest rate attained in reproducible fashion was estimated to be 3.4×10^6 tritium atoms per second.

3.2. Experiments on detection of T in the electrolysis of D_2O by the group at the Texas A&M University

In a recent experiment of the group of J. Bockris[11] the standard method of electrolysis in an open-type cell was used

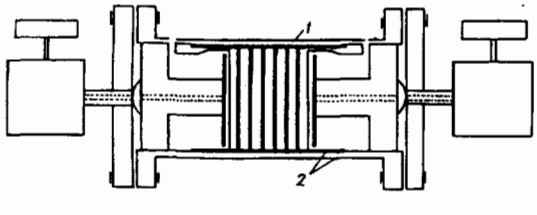

FIG. 11. Pd–Si–D_2 cell.[10] *1*—layers of Pd and Si, *2*—ceramic insulation.

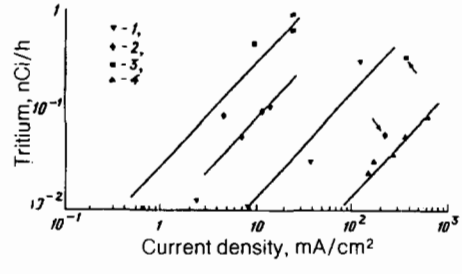

FIG. 12. Formation of tritium in the Los Alamos experiment[10] correlated with the current density and type of cell. *1*—no oxide layer, *2*—natural oxide layer, *3*—increased oxide layer, *4*—foil and "waffles;" arrows–breakdown.

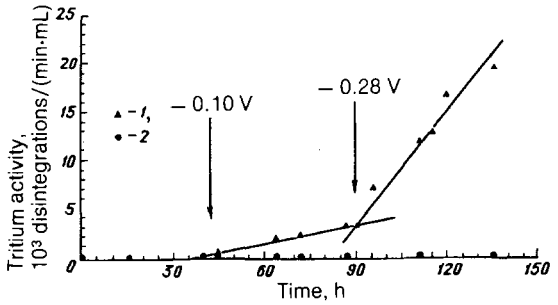

FIG. 13. Dependence of the tritium activity on the time of electrolysis.[11] Triangles–working cell, dots–control cell; the arrows indicate the instants of changing the voltage.

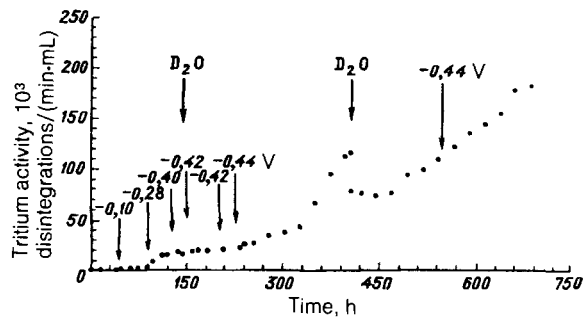

FIG. 14. Dependence of tritium activity in the working cell on the time of electrolysis; the arrows indicate the instants of changing the voltage and adding D_2O.

with an electrolyte of D_2O + 0.1 M LiOD. The Pd cathode amounted to a cylinder 1.6 cm long with diameter 1 cm. The total duration of the measurements amounted to 760 h.

Figures 13 and 14 show the results of the measurements of the tritium activity of the electrolyte in the process of electrolysis. The initial charging at the small cathode potential of -0.05 V and $j \leqslant 0.1$ mA·cm^{-2} for 30–40 h showed no increase of T above background (12 ± 3 disintegrations/(min·mL)). After increasing the cathode potential U to -0.10 V, a reaction of T formation was detected with the rate $\dot{N}_T \approx 2.1 \times 10^6$ T atoms/(s·cm^2)). As we see from Fig. 14, when U was increased, a further increase in the rate of T formation occurred. The greatest rate, 3.8×10^7 T/(s·cm^2), was obtained after 327 h of electrolysis. The reaction was suppressed at 406 h after adding D_2O and then restored after 471 h without increasing the potential. However, further increase in U did not lead to an increase in $\dot{N}_T$. After 760 h the electrolysis was stopped. Subsequent attempts with the same electrode to restore T formation had no success. The results are summarized in Table VIII.

Since the greatest criticism of the results of measurements of T involved possible impurities in the original materials, the authors performed a series of control measurements.

a) Three measurements of T in specimens from the same lot used in the experiment.

b) Several specimens were sent for analysis for ^{3}He to the experts of Rockwell International. No impurities of ^{3}He above the background level (10^9 ^{3}He) were found. This is an argument favoring the idea that the main mass of T found in the electrolyte was formed in the course of the experiment and was not a result of tritium impurities in the original materials.

c) Comparison with a control cell that did not exhibit T formation gave a limitation on the possible trapping of T from the surrounding air.

d) The fact that the electrode after 760 h ceased to form T also indicates against possible trapping of T from the air.

The examples given above of detection of LFT by measuring tritium look rather convincing. (We recall that in all more than 40 reports have been published up to now in the literature on the detection of anomalous formation of tritium upon electrolyzing D_2O.[12] Here in $\approx 20\%$ of the studies the measured amount of tritium exceeded the background by a factor of 10^2–10^4.) However, actually, the situation is far from being so unambiguous. The point is that the use of a signal of LTF of such a widespread nuclide as tritium possesses a number of negative features as compared with direct observation of nuclear effects in a real-time regime.[6] It is very difficult to avoid impurities and contamination. One of the source materials of the experiments on LTF–D_2O (or D_2) always contains an admixture of tritium. Although the amounts of T atoms reported in the literature are large, the sensitivity of the measurements is many orders of magnitude smaller than in detecting neutrons. As was noted in Ref. 13, the use of an open cell also can lead to false effects. Reference 6 pointed out possible sources of errors in tritium measurements from β-decay: a) detection errors, including chemiluminescence and incorrect determination of the

TABLE VIII. Results of analysis for tritium.[11]

T in the electrolyte	T in the gas (assuming that $T_g/T_l = 5$)	T in Pd (solution in aqua regia)	T in Pd (anode discharge)
1.6×10^{14} T atoms	8.1×10^{14} T	5.1×10^9 T/g Pd	8×10^9 T/g Pd
Or 1.5×10^{13} T/g	Or 5.4×10^{13} T/g	Or total number in Pd	Or total number in Pd
Or 2.55×10^{13} T/cm^2	Or 1.2×10^{14} T/cm^2	7.6×10^{10} T	1.2×10^{11} T

The total number of T atoms formed in the electrolyte, gas, and metal is 10^{15}T atoms or 6.9×10^{13} T/g, or 1.5×10^{14} T/cm^2.

background; b) "external" contamination, which is especially probable in laboratories performing tritium experiments; c) "homogeneous" contamination of the materials of the cell; d) "inhomogeneous" (localized in isolated regions of the specimens) contamination; e) increase in T content owing to the natural factor of T/D separation. To eliminate the various false effects requires various control experiments. For an unambiguous identification of T by β-decay, it does not suffice simply to count the pulses from the counter. One must measure the stable, reproducible energy spectrum with a correct shape and maximum energy.

It is especially difficult to eliminate false effects due to localized T impurities in the original metal. To do this, one must perform a careful analysis of a large number of test specimens taken from different regions of the material. Such an analysis was performed by the group of K. Wolf[6] and revealed the presence of T in the original Pd in the form of very small isolated "spots" having a high concentration of T. The series of measurements performed by this group with 100 cells showed an excess of T in only two of them. In the opinion of the authors, this can be fully explained within the limits of statistics as resulting from occluded impurities in the Pd. After these experiments K. Wolf rejected his preliminary results on T that had been performed earlier jointly with J Bockris, in which a painstaking study of the source materials had not been carried out.

4. DETECTION OF ^{4}He

Recent reports of detection of a gain in ^{4}He upon electrolysis aroused great interest and animated discussion.

4.1.

The group of researchers from the University of Texas at Austin and the Naval Weapons Laboratory (China Lake) performed calorimetric measurements and analysis for ^{4}He of the gases released in the electrolysis of D_2O + LiOD on Pd.[14] It was found that the gases formed contain ^{4}He in those cases in which a considerable excess heat was detected in the electrolysis. Moreover, darkening of x-ray films placed near the two working cells was found. A control experiment with H_2O + LiOH revealed neither ^{4}He nor film darkening.

The experiments employed a cryofilter containing activated charcoal, which enabled removing interfering impurities of D_2 and O_2 from the gases released upon electrolysis and to identify ^{4}He unambiguously with a precision mass spectrometer. Although the nature of the reaction leading to the generation of heat and ^{4}He is unknown, the authors used as the basis of estimates the process $d + d \rightarrow {}^4He + \gamma + 23.4$ MeV, for which an energy release of 1 W corresponds to the formation of 2.66×10^{11} ^{4}He atoms per second. The greatest excess heat that they found, 1.3 W/cm^3, corresponds to 5.4×10^{14} ^{4}He atoms in the time necessary for filling the test volume of 500 cm^3. The amount of ^{4}He that was found exceeds by more than two orders of magnitude the limit of sensitivity of the method that was used. The authors treated the observed correlation of the excess heat and the formation of ^{4}He as a strong argument favoring a nuclear nature of the processes leading to energy release in the electrolytic experiments.

4.2.

The group of researchers at the University of Hawaii[15] performed an experiment on electrolysis of LiOD in a KCl salt melt at a temperature of $\gtrsim 350$ °C and a current of 700 mA/cm^2 with anodes of Pd and Ti and an aluminum cathode. In the four Pd specimens the formation of ^{4}He was found by mass spectrometry at a level up to 14σ above background. For the entire electrode this corresponds to an excess above background of 4×10^{10} ^{4}He atoms. This is substantially smaller than follows from the excess heat release found in this same experiment if the reaction $d + d \rightarrow {}^4He + \gamma$ is responsible for it. Over four days an excess heat release was measured at the level $\Delta Q/Q \sim 500$–1500% of the supplied energy. The maximum effect amounted to 25 W or 600 W/cm^3.

4.3.

In the experiment described above, the group of J. Bockris also detected the formation of ^{4}He in the electrolysis of D_2O at a Pd electrode. The results of the analysis performed at the Rockwell International laboratory are presented in Table IX.

TABLE IX. Results of analysis for ^{4}He of Pd specimens subjected to electrolysis in D_2O.[11]

Specimens near the surface		Specimens far from the surface	
Mass of specimen, mg	$He^4/10^9$ (or 10^{11} g)	Mass of specimen, mg	$He^4/10^9$ (or 10^{11}/g)
1) 30.92	3.8 ± 0.3 (1.2 ± 0.1)	27.79	1.9 ± 0.3 (0.7 ± 0.1)
2) 39.70	166.8 ± 3.3 (42 ± 0.8)	30.01	2.5 ± 0.3 (0.8 ± 0.1)
3) 42.37	3.4 ± 0.3 (0.8 ± 0.1)	23.85	0.4 ± 0.3 (0.17 ± 0.12)
4) 20.22	2.1 ± 0.6 (1.0 ± 0.3)	33.05	1.7 ± 0.6 (0.5 ± 0.2)
5) 44.63	1.9 ± 0.5 (0.4 ± 0.1)		
6) 30.40	-0.1 ± 0.5 (0.03 ± 0.1)		

Mean background value: 0.5×10^9 ^{4}He atoms.

4.4.

At the conference at Half Moon Bay the group from Rockwell International presented the results of analysis of Pd specimens and of released gases for five experiments on LTF in which the generation of ^{4}He was found according to the statement of the authors. The group used a helium mass spectrometer, which is the unique national installation designed for performing measurements of very small concentrations of helium in solids and various aqueous solutions. The dynamic range of the measurement was from a few percent to 10^{-12}. Here one can attain a level of accuracy of 1% almost throughout the region. Moreover, the installation enables one to perform precision measurements of tritium by detecting the product of its decay–^{3}He. The accuracy of the measurements for Pd was tested in special control experiments with specimens saturated by the method of ion implantation (six Pd foils were saturated with doses of 10^{10}–10^{11} atoms of ^{4}He); the mass spectrometer made it possible to detect the presence of ^{3}He or ^{4}He at the level of 10^9 atoms. This corresponds to a detection level of 6×10^{11} atoms per cm^3 of Pd. For the hypothetical reactions of dd fusion this corresponds to the following level of energy release:

$$d + d \rightarrow \begin{cases} ^3\text{He} + n + 3.3\,\text{MeV}, \\ T + p + 4.0\,\text{MeV}, \\ ^4\text{He} + \gamma + 23.8\,\text{MeV} \end{cases}$$

and

$$\Delta\dot{Q} = \begin{cases} 0.3\ \text{J/cm}^3\ \text{Pd} \\ 80\ \text{J/cm}^3\ \text{Pd} \\ 2.3\ \text{J/cm}^3\ \text{Pd} \end{cases}$$

respectively.

The group performed about 300 measurements of palladium specimens obtained from 16 laboratories and universities that had performed experiments on LTF. In none of them was a measurable amount of ^{3}He atoms detected.

In some specimens obtained from the following five laboratories the presence of ^{4}He was found above the sensitivity threshold of the spectrometer (5×10^8 atoms): the University of Utah (Fleischmann and Pons), ETEC (Leadville); experiment with muons), University of Hawaii (melt of salts), "Luch" (Podol'sk, gas discharge in D_2), and Texas A&M University (Bockris).

Let us study as an example the results of analysis of five rods prepared by Fleischmann and Pons. Three of them had been subjected to ion implantation with helium with various doses; two of these rods were then subjected to electrolysis—one in LiOH, the other in LiOD. One of the rods was not subjected to any saturation. Finally, the last rod was subjected to electrolysis in LiOD (without implantation). Individual specimens from different regions of the rods were subjected to analysis in five independent laboratories. Not one of them revealed the presence of ^{3}He; ^{4}He was found by all five laboratories in all five rods (Table X). The conclusions of the Rockwell International group were:

—Implanted helium was not removed from Pd by subsequent electrolysis.

—^{4}He in the electrolyzed rod and in the rod not subjected to saturation with deuterium was completely contained in an outer layer $\lesssim 25\ \mu$m.

—the level of ^{4}He found after electrolysis was higher than in the unprocessed rod, but still was too low to explain the excess heat in the experiments of Fleischmann and Pons.

—the presence of ^{4}He in the unprocessed specimen renders the interpretation of the entire experiment very difficult.

The latter situation was manifested even more strikingly in the analysis of the Pd from the experiments of the University of Hawaii. In two specimens from the rod subjected to electrolysis $(0.7\pm0.3)\times10^9$ and $(6.2\pm0.3)\times10^9$ atoms of ^{4}He were found, whereas from the unprocessed rod (obtained from the same supplier) $(15.0\pm0.3)\times10^9$, $(12.5\pm0.3)\times10^9$, and even $(195.3\pm3.9)\times10^9$ ^{4}He atoms were detected. Perhaps this serves as a confirmation of the result already mentioned above of the group of Wolf of the very inhomogeneous distribution of impurities and localization of them in individual regions of the specimens.

The authors indicate also possible reasons for the excess of ^{4}He. In the experiments of the Texas-China Lake group this can be diffusion of ^{4}He through the walls of the control glass flask from the surrounding air. In the experiment of the

TABLE X. Results of analysis[16] for ^{3}He and ^{4}He of five specimens prepared by Fleischmann and Pons.

Rod number	Processing of specimen	Mass of specimen, mg	Results of measurements	
			^{3}He	^{4}He
1	Ion implantation,	8.79	$<1\times10^{11}$	5.10×10^{14}
	electrolysis in LiOD	7.15	$<1\times10^{11}$	4.14×10^{14}
2	Unprocessed specimen	19.13	$<3\times10^{8}$	3.53×10^{10}
		24.57	$<3\times10^{8}$	3.00×10^{10}
		28.07	$<3\times10^{8}$	6.01×10^{10}
		21.23	$<3\times10^{8}$	3.79×10^{10}
3	Ion implantation	5.97	$<1\times10^{11}$	8.91×10^{13}
		5.08	$<1\times10^{4}$	1.18×10^{14}
4	Ion implantation,	10.00	$<1\times10^{11}$	3.08×10^{14}
	electrolysis in LiOH	6.66	$<1\times10^{11}$	1.74×10^{14}
5	Electrolysis in LiOD	24.30	$<2\times10^{8}$	2.84×10^{11}
		17.55	$<2\times10^{8}$	1.17×10^{11}
		26.64	$<3\times10^{8}$	2.26×10^{11}
		16.27	$<3\times10^{8}$	9.80×10^{10}

"Luch" group it can be an impurity of ^{4}He in the D_2 in the gas discharge.

The Rockwell International group is continuing its measurements (in particular, the materials of Bockris *et al.*). Therefore their conclusions are preliminary in character. Nevertheless they emphasize the following circumstances:

—the need for analysis of control materials subjected to electrolysis in H_2O;

—the need for vacuum treatment of the Pd to remove residual impurities of hydrogen isotopes to exclude their interference in analyzing for ^{4}He;

—it is not yet clear whether the presence of ^{4}He observed in certain specimens is due to LTF reactions or to impurities; however, it is quite evident that the observed amounts of ^{4}He are too small to explain the heat effects claimed by certain authors.

5. THEORETICAL MODELS OF LTF

The three-year history of the development of studies on LTF has shown that the problem of theoretical description of the mechanism of this phenomenon has proved no less complex than the obtaining of unequivocal experimental conclusions. Consequently the situation in the theoretical field remains just as unclear as in experiment.

At present there is no consistent theory that would predict LTF and its features starting from first principles. Therefore it is quite natural that the discussion of the mechanism of LTF is being conducted on the basis of various models based on various initial physical hypotheses.

The total number of published models is very large. Here I shall restrict the discussion to only a general, brief summary of my understanding of the situation in the theory. One can find a more complete critical discussion of the various models of LTF and references to the original studies in the review of Ref. 17 (see also the earlier reviews of Refs. 1, 2, 8, 12, and 18).

A highly substantial role in the construction of models (explicitly or implicitly) is also played by the "methodological" aspect. Although ultimately all the theoretical studies are motivated by the attempt to explain experiment, an important difference consists in the degree of criticism (or faith) toward the existing experimental results. Some authors are inclined to accept as given the entire set of published results, including excess heat release, predominance of tritium, neutron bursts, etc. In this case the problem consists in explaining all these effects within the framework of a unitary approach. Others prefer to maintain a more cautious attitude toward experiment. Their aim is to understand, having adopted some physical hypothesis, what observable consequences are possible on its basis.

If we examine the different models proceeding along the scale of characteristic energies from small ($\lesssim 1$ eV), corresponding to "true cold" fusion, to moderate ("warm" fusion with $E \sim 1$–100 eV), and then large (~ 1–10 keV), corresponding to "hot" fusion, it turns out that this sequence corresponds to a considerable degree to movement from more exotic models that assume a "new physics" to simpler and more "natural" models.

The considerable number of attempts involves the initial hopes of achieving continuous fusion under steady-state conditions in a lattice (for more details see Ref. 1). In this regard various configurations of interatomic fields and screening effects have been studied from the standpoint of approach of deuterium nuclei at thermal energies to distances ~ 0.1 Å $\ll R_{D_2}$ adequate to explain the observed rate of fusion. The overall result of these studies is negative. Moreover, from highly general considerations based on the analysis of the binding of ^{4}He in metals, rigid restrictions have been obtained of the possible effects of enhanced screening of the d-d Coulomb barrier in metals in the equilibrium state.[19]

Among the models that claim to explain the entire set of experiments on LTF we can distinguish two categories.

In one of them the common feature is the assumption of some specific quantum-mechanical effects in the crystal lattice that lead to a substantial increase in the rate of fusion. In some models center stage is taken by the periodic character of the interatomic fields in crystals, in others by specific conditions in individual regions of the lattice–defects, bands of "quantum-electromechanical confinement," etc. Unfortunately, as was shown in Ref. 17, all the studies of this type that we know prove to be incorrect from the theoretical standpoint, and hence cannot be used to explain LTF.

The models of another group are based on highly exotic hypotheses that are very difficult to test at present. An example is the hypothesis of the existence of new, very heavy stable particles that effect catalysis of LTF (by analogy with muon catalysis). Although in principle this hypothesis can have the right to existence, at the same time, the attempt to explain the incomprehensible mechanism of LTF by using even more exotic objects can arouse dissatisfaction, and all the more in that many properties of such particles are not fixed by the existing models. This leaves broad leeway for their authors to play a game, the rules of which they themselves establish. In this sense, e.g., the model of catalysis by heavy particles can count on being taken seriously either if such particles are discovered experimentally or if sufficiently grounded and rigorous tests for LTF that eliminate the arbitrariness of the predictions are formulated.

A more "moderate" hypothesis is that of the existence of some metastable compound system of two deuterons whose appearance precedes nuclear fusion. Such systems might be formed owing to electromagnetic forces (in the lattice) or nuclear interactions, and enhance the rate of fusion.

Actually no grounds can be seen for the existence of a "binuclear atom" $(D^+D^+)2e^-$ or a "superbound state" $(D_2^+)^*$. If instead of suggestive ideas we use the exact solution for the given systems, then we arrive at a smooth potential that contains no metastable levels. As was shown in Ref. 20, the existing data on the cross sections of dd and dT reactions are sufficient to obtain a reliable extrapolation to extremely small energies and to rule out the influence of hypothetical nuclear resonances that might explain the observed rates of LTF.

Among the most "natural" and developed models are the "accelerator" models (see Ref. 1). They are based on the idea of overcoming the Coulomb barrier via energy acquired by the deuterium ions as they are accelerated in various processes in the lattice or on the surface of the specimens. Thus, the accelerator models belong to the category of "hot" models, with characteristic energies $\sim 10^2$–10^4 eV.

The accelerator models have a number of problems involving the need for strong fields in cracks and a relation of the time scales characterizing the different competing pro-

cesses, but these problems apparently can be overcome within the framework of rather natural assumptions that allow experimental verification.[1] Within the framework of these models one can qualitatively explain all the observed features of neutron emission and quantitatively correlate its rate with the amplitudes of the "accompanying" signals of electromagnetic and acoustic emission. However, neither the enormous predominance of tritium (or helium) nor the excess heat release can be described within the framework of the accelerator mechanism.

6. CONCLUSION

The results presented above of a number of recent experiments to detect the products of LTF and some attempts at theoretical description of the mechanism of LTF, as it seems to us, confirm the estimate of the situation given in the Introduction: the studies on LTF as still at the stage when it is premature to draw final conclusions.

The most reliable observations are those of weak anomalous neutron emission (on the average at the "Jones level"). The better experiments of this category were performed by using contemporary nuclear-physical technique and painstaking analysis of the different sources of interference and false effects. Apparently their results do not arouse especial doubts. However, conditions have still not been found that unambiguously guarantee the onset of this emission, which is observed only in a small number of the studied specimens.

The situation is less definite in the detection of tritium and helium. Although the presence of these isotopes in experiments on LTF has been established rather reliably, as yet one cannot completely rule out false effects caused by localized impurities in the original materials and by trapping from the surrounding medium.

It has also not been possible to achieve a theoretical description of LTF that would explain the entire set of data obtained by the different experimental groups. Perhaps such an explanation will be found sooner or later. However, it is not ruled out that such a situation is not fortuitous and reflects the contradictoriness and incorrectness of some part of the experiments. In this regard we stress again that the models known to us that claim to explain the excess heat release and $T/n \gg 1$ are either unsatisfactory from the theoretical standpoint or are based on highly exotic assumptions that have no experimental grounding, which renders them hardly realistic. Among the known models actually only the models of accelerator type are sufficiently simple and natural and do not require the introduction of a new physics. However, such models can explain only the anomalous low-intensity nuclear phenomena that do not lead to excess heat release and to $T/n \sim 1$. Further precision measurements should show whether the phenomenon of LTF is actually reduced to these effects, or there actually exist such unusual effects as excess heat release and predominance of tritium and helium.

[1)] Two conferences were held in 1991 on the problematics of LTF (in March at Dubna and in June at Como, Italy), and two workshops (in November at Ekaterinburg and in December at Half Moon Bay, California, USA).

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