Detection of High Energy Particles Using CR-39 Detectors Part 1: Results of Microscopic Examination, Scanning, and LET Analysis

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Abstract

CR-39 detectors were used to detect high energy particles produced during Pd/D co-deposition. Upon completion of the experiments, the detectors were subjected to either microscopic examination, scanning using an automated scanner to obtain quantitative information on the tracks, sequential etching, or linear energy transfer (LET) spectrum analysis. Both the sequential etching and LET analysis allowed speciation of the particles that caused the tracks as well as estimating their energies. In these experiments it was shown that the tracks coincide with the placement of the Pd deposit. The average number of tracks obtained as a result of

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Pd/D co-deposition is more than 133 times greater than that found in the background. In this communication, the results of microscopic examination, scanning, and LET analysis are discussed.

KEYWORDS: palladium; nuclear particles; CR-39; LET spectrum; energy distribution

1.0 INTRODUCTION

Recently Holmlid and Olafsson [1] reported the detection of high energy particles from spontaneous processes occurring in an ultra-dense deuterium D(0) layer. They also speculated that low energy nuclear reactions (LENR) may also give rise to such particles. Consequently, any experiments that show the emission of energetic particles would support this supposition. There have been previous reports of tritium [2-17], neutrons [8, 9, 13, 14, 18-28], charged particles [29-31], and helium-4 [32-36] generated electrochemically using either Pd or Ti cathodes. A review of nuclear products generated as a result of LENR experiments [37] summarizes the nuclear products that have been detected using various methods in both electrolytic and gas loading experiments. Of the nuclear products generated, only helium-4 correlated with the production of excess heat [35]. The nature of the reactions that have produced these energetic particles is not fully understood. The particles observed and their energies are consistent with DD primary and secondary reactions. What is known is that, in order to induce the effect, the deuterium needs to be contained within a metal lattice, the D/Pd loading is ≥ 0.9 , and that there is deuterium flux inside the lattice. Enhancements in DD reactions in metal lattices have been observed in accelerator experiments [38, 39]. The observed enhancements in the reaction was larger than the theoretically calculated Gamow Factor, indicating that electron screening plays a significant role in increasing fusion rates at low energies. However, the observed cross section enhancements observed in these accelerator experiments was significantly larger than could be accounted for by electron screening alone [40]. These observations suggest that there is an additional mechanism of the screening that enables deuteria to tunnel through the Coulomb barrier.

The emission of energetic charged particles during Pd/D co-deposition has been reported [41]. To detect these high energy particles, the solid state nuclear track detector (SSNTD), CR-

39 was used [42]. CR-39, an allyl diglycol carbonate with a chemical composition of $C_{12}H_{18}O_7$, is sensitive to charged particles with high LET (≥ 3 keV/ μ m CR-39). When low energy protons, heavy charged particles, fast protons or secondary heavy charged particles from neutron recoils traverse CR-39, they break the polymer molecular bonds forming highly reactive paths along their trajectories. These paths can be revealed as cones on the surfaces of the detectors after chemical etching. The optical properties of the tracks resulting from Pd/D co-deposition were consistent with those of nuclear generated tracks [43]. A series of control experiments showed that the tracks were not due to radioactive contamination of the cell components nor were they the result of either chemical or mechanical damage. This experiment has been very reproducible. We have done close to fifty experiments using different substrates to plate on, with and without external fields, as well as different cell configurations [41, 43, 44] and have gotten the same results. These experiments were replicated by three groups of senior chemical engineering undergraduates at the University of California San Diego [45].

In this effort, Pd/D co-deposition experiments were conducted at SRI with the CR-39 detectors inside the cell in contact with the cathode and outside the cell. The detectors used in the immersion experiments were designated 10-5 and 10-6. In the outside the cell experiments, the CR-39 detector and cathode were separated by a 6 μ m thick Mylar film. This detector was designated 10-7. Upon completion of the experiments, the etched CR-39 detectors were analyzed independently by us and a group led by the Lebedev Physics Institute (LPI). Our group subjected detectors 10-5 and 10-6 to microscopic examination, scanning using an automated scanner, and linear energy transfer (LET) spectrum analysis while the LPI led group subjected detectors 10-5 and 10-7 to sequential etching analysis. The purpose of the LET spectrum analysis and the sequential etching analysis was to speciate and determine the energies of the high energy particles that were generated as a result of Pd/D co-deposition. In this communication, the results of the microscopic examination, scanning, and LET spectrum analysis of detectors 10-5 and 10-6 are discussed. Sequential etching analysis of detectors 10-5 and 10-7 are discussed in the second communiqué. As will be shown, the two disparate methods of analyzing the detectors yield similar results.

2.0 EXPERIMENTAL

2.1 Materials

Palladium chloride (Aldrich), lithium chloride (Mallinckrodt), deuterated water (Aldrich), HPLC grade light water (Aldrich), sodium hydroxide (Aldrich), copper chloride (Aldrich), 0.25 mm diameter silver wire, 0.5 mm diameter silver wire (Aldrich), and 0.25 mm diameter platinum wire (Aldrich) were used as received. CR-39 detectors (Fukuvi), rectangular in shape with dimensions of 1 cm $\times$ 2 cm $\times$ 1 mm, were obtained from Landauer and used as received.

2.2 Cell Design and Charging Procedure

A schematic of the rectangular, butyrate cell in Figure 1a shows the orientation of the anode, cathode, and NdFeB magnets employed in the experiments done at SRI using detectors 10-5 and 10-6. The strength of the magnetic field was 2500 Gauss. The magnetic field was present throughout the course of the experiment. Previous experiments done by us and others [46, 47] have shown that the presence of an external magnetic field results in increased heat production. This suggests that a magnetic field enhances the effect.

A schematic of the cathode is shown in Figure 1b. The cathode consists of a single 16 cm long, 0.25 mm diameter Ag wire wrapped serpentine around a CR-39 detector (Fukuvi) as shown in Figure 1b. Of this, ~4.2 cm of the wire was in contact with the plating solution. The exposed surface area of this Ag wire was 0.33 cm². A 60 μ m thick polyethylene film separated the cathode from the CR-39 detector. This film protected the surface of the detector from mechanical and chemical damage. A solution of 0.03 M PdCl₂ and LiCl in D₂O was added and Pd was plated out onto the Ag wire. The charging profile was 0.2 mA for one day followed by 0.5 mA until the solution cleared. This assured good adherence of the Pd onto the Ag wire. Once plated out, the cathodic current was increased, in a stepwise fashion, to 1 mA for 48 h, 5 mA for 20 h, 10 mA for 28 h, 25 mA for 60 hr, and 100 mA for 36 h. The surface area of the electrode is estimated to increase by approximately a factor of 10x after Pd deposition has completed.

A control experiment using CuCl₂ in place of PdCl₂ was done by the authors. The SRI protocol was followed in the control experiment. Specifically, a 60 μ m thick polyethylene film separated the cathode from the CR-39 detector and a magnetic field was present throughout the

course of the experiment. The current-time profile described above was used once all the copper had plated out.

2.3 Etching, Microscopic Examination, and Scanning of CR-39 Detectors

At the end of each experiment, the polyethylene film was removed and the CR-39 detector was etched in 6.5 N NaOH at 65 °C for 7 h. Microscopic examination of the etched CR-39 detectors was done using an Eclipse E600 epifluorescent microscope (Nikon) and CoolSnap HQ CCD camera (Photometrics). Magnifications of 200X and 1000X were used. The software used to obtain the images was MetaVue (MDS Analytical Technologies).

Scanning of the CR-39 detectors was done using a TASL Image system (Track Analysis Systems, Ltd, Bristol, UK) to obtain quantitative information on the pits produced in the CR-39. The system has a high quality microscope optical system (Nikon cfi series) operating at a magnification high enough to discriminate between tracks and background. The images obtained were then analyzed by the proprietary software. The software makes 15 characteristic measurements of each feature located in the image to provide reliable discrimination between etched tracks and background features present on or in the plastic detectors. These measurements include track length and diameter, optical density (average image contrast) and image symmetry. Based upon the measured properties of a feature, the software of the automated scanning system determines whether or not the measured features are consistent with that of an energetic particle. The software algorithms ignore overlapping tracks. The scanned data for both detectors are provided in the supplementary material.

2.4 LET Analysis of CR-39 Detectors

In CR-39, the linear stopping power, $(dE/dx)_{elec}$, contributed by atomic collisions of charged particles, where ‘elec’ specifies electronic (atomic collision), is related to the restricted energy loss (LET). The LET is defined as $L_{\Delta} = dE_{\Delta}/dx$, where dE_{Δ} is the energy loss by a charged particle due to electronic collision, minus the sum of the kinetic energies of all the electrons released with kinetic energies in excess of Δ . For CR-39, electrons with energies greater than $\Delta=200$ eV don’t form tracks. The restricted energy loss is often written as LET_{Δ} and the

unrestricted energy loss as LET_{∞} . The LET_{Δ} for the $\Delta=200$ eV is often noted as LET_{200} . The LET values reported here are LET_{200} , denoted as LET (keV/ μ m CR-39).

As indicated *vide supra*, there is a preferential, or faster etch, along the direction of a particle's trajectory where the polymer has been damaged by the energy deposited. The chemical etching forms cones on the surface of CR-39 detector that are observable with an optical microscope. In order to determine the bulk etch rate, the thickness and the mass before and after etch for the CR-39 plate were measured and the bulk etch B , the thickness etched off on one surface of the CR-39 detector, was calculated by Henke's formula [48]:

$$B = \frac{(m_1 - m_2)T_2}{2m_2} \left(1 - \frac{pT_2}{2A_d}\right) \quad (1)$$

where m_1 is the detector mass before etch, m_2 , the mass after etch; T_2 , the average detector thickness after etch; p , the detector perimeter and A_d , the detector surface area.

The etch rate ratio is defined as $S=V_T/V_B$, where V_B is the etch rate of the undamaged regions of the detector (bulk etch rate) and V_T is the track etch rate defined as $V_T=L_o/t$, where L_o is the length from pre-etch surface to the etched cone tip measured along the particle's trajectory and t is the etch time. The etch rate ratio can be calculated with Somogyi's formula if the etched cone is conical [49]:

$$S = \sqrt{1 + 4\left(\frac{a}{2B}\right)^2 \left[1 - \left(\frac{b}{2B}\right)^2\right]^2} \quad (2)$$

where a and b are the major and minor axes of the etched cones respectively that are measured during the automatic scanning. LET values for measured charged-particles can be calculated using LET calibration for CR-39 detectors.

The relationship between LET_{200} in CR-39 and the etch rate ratio S was determined by calibrating CR-39 detectors using heavy ions and protons with different energies generated by different accelerator centers for CR-39 manufactured by American Technical Plastics [50]. The LET_{200} CR-39 values of calibration particles can be calculated either by Benton table [51] or by computer codes [52] and, S values can be calculated with Somogyi formula. Although CR-39 material manufactured by different companies etches differently as a function of the

manufacturing processes, the LET calibrations are based upon the CR-39 chemical formula and are essentially identical. The research work using CR-39 detectors in DIAS (Dublin Institute for Advanced Studies, Ireland), NASA-JSC (Johnson Space Center) and NSSC (National Space Science Center, Chinese Academy of Sciences) has shown that the LET calibrations for CR-39 are consistent and independent of manufacturing due to the identical CR-39 chemical components. Therefore, the LET American Technical Plastic CR-39 calibration [50] was used for the Fukuvi CR-39 employed here.

For each track, or scanned event, the etch rate ratio was calculated, using the major and minor axes measured for each track, and the LET value was determined and binned, then the differential fluence spectrum was generated. The differential fluence for the particles recorded can be expressed as

$$f = dN(i)/[A_S \times dLET(i)] \quad (3)$$

where A_S is the scanned area of CR-39 detector, $dN(i)$ is the number of particles in the i th LET bin $LET(i)$ with a bin width of $dLET(i)$. The net differential fluence for LENR particles is obtained by subtracting the background (radon α particles, ground cosmic rays, and defects of CR-39 material) from the total differential fluence. However, as will be shown *vide infra*, the LENR background is low and can be ignored. The integral spectrum of fluence is generated by summing the differential spectrum from high LET to low LET. In the LET method of analysis for CR-39 detectors, the error in the LET calculations is mainly due to the measurement errors of the dimensions of the detector and the track cone surfaces. For the mass difference method used for the bulk etch calculation, the relative error of the bulk etch is $< \sim 1\%$. If the automatic data scan is used, as was done in these analyses, the relative error for the dimensions of the track cone surface is also $< \sim 1\%$. Therefore, the error of the LET calculations resulting from the measurements can be ignored. Additional details on the LET spectrum method using CR-39 detectors and its applications can be found in references [53-61].

3.0 RESULTS AND DISCUSSION

3.1 Microscopic Examination of the CR-39 Detectors

The Fukuvi CR-39 detectors come covered on both sides with a 60 μm thick polyethylene film. In the SRI replication, this film was between the cathode and the detector. Linear energy

transfer (LET) calculations [62] indicate that 60 μm thick polyethylene will block 7 MeV alphas and 1.8 MeV protons. Consequently, the 60 μm film greatly reduces the number of tracks, as shown in Figure 2.

After etching, detectors 10-5 and 10-6 were examined microscopically. Figure 3a shows a photomicrograph of detector 10-5 obtained at 200 $\times$ magnification showing the density of tracks obtained. The observed high density of tracks implies a high flux rate. However, these experiments typically last between one to two weeks and CR-39, like photographic film, is an integrating detector. When an event occurs, it is permanently stamped in the plastic of the detector. As a result, the signal does not get averaged away and the spatial distribution of the events can be determined, however, it is not known when the event(s) occurred. At 1000 $\times$ magnification, top image in Figure 3b, it can be seen that there are dark, circular and elliptical tracks. There are also smaller, shallower tracks which are due to either latent tracks deeper inside the plastic, or to particles that barely impact the detector, or to highly energetic charged particles. When the microscope optics were focused on the bottom of the tracks, bottom image in Figure 3b, bright spots are observed inside the tracks. These bright spots indicate the endpoints of the particles that enter the detector and are caused by the curved bottom of the track acting like a lens when the detector is backlit [63]. The color, shape, and bright spot inside are features consistent with those observed for nuclear generated particle tracks.

To provide further experimental evidence that the observed tracks in Figures 2 and 3 were not due to chemical damage, a control experiment was done using a polyethylene coated CR-39 detector and electroplating using CuCl_2 instead of PdCl_2 . For both CuCl_2 and PdCl_2 , the same electrochemical reactions occur at the anode and cathode. Specifically, oxygen and chlorine gas evolution occurs at the cathode while deuterium gas evolution and metal electroplating occur at the anode. In addition, the resultant Cu and Pd metallic deposits exhibit similar dendritic morphologies. The only significant difference is that Pd absorbs deuterium and Cu does not. No tracks were observed for the CuCl_2 experiment. This experiment indicates that the tracks observed in the PdCl_2 experiment cannot be attributed to a chemical species diffusing through the polyethylene film that attacks the surface of the detector. If this were the case, the CR-39 detector used in the CuCl_2 experiment would have exhibited cloudiness and pitting, which it did

not. The results also indicate that the Cu dendrites did not pierce through the polyethylene cover and into the detector. It can therefore be concluded that the observed pitting in the PdCl_2 system is not due to either chemical or mechanical damage of the CR-39 detector.

3.2 Results of the Automated Scanning

Prior to microscopic examination and scanning, photographs of the CR-39 detector 10-5 were taken before and after etching. A photograph of the polyethylene-covered CR-39 detector 10-5 at the end of the experiment is shown in Figure 4a. Arrows indicate the placement of the Ag wires. The dark areas on the polyethylene cover are due to the Pd deposit. These dark areas indicate that the Pd deposit extended past the Ag wires and into the areas between the wires. Figure 4b shows a photograph of the front surface of the detector 10-5 after etching. The white, cloudy areas are due to high track density. It can be seen that the density of tracks is highest near the vicinity of the Pd-coated Ag wires indicating that the cathode is the source of these tracks. Ohmic measurements using probes on both sides of the polyethylene film indicate that the deposit did not go through the 60 μm thick polyethylene film. These measurements indicate that the Pd dendrites did not pierce through the polyethylene film and into the CR-39 detector.

After microscopic examination of the CR-39 detectors 10-5 and 10-6 was completed, the front and back surfaces of the detectors were scanned using an automated scanner. As discussed *vide supra*, the scanner uses a high quality microscope optical system operating at a magnification high enough to discriminate between tracks and background. Figure 5 illustrates how the automated system works. Figures 5a and 5b are scanner images taken of the CR-39 detector 10-6 used in the SRI replication. To obtain the images shown in Figures 5a and 5b, the microscope optics were focused on the surface of the detector and the bottom of the pits, respectively. In Figure 5b, bright spots are observed inside the pits. The objects in the image were then identified by the system, Figure 5c. Fifteen measurements of each object in the image were then made by the system. These measurements include track diameter and length, optical density (average image contrast), and image symmetry. The system then uses image analysis algorithms to discriminate between etched tracks and background features. Based upon those measurements and the image analysis algorithms, some of the objects in the image were identified as nuclear particle generated tracks. These are designated by the light colored squares

in Figure 5d. The objects designated by the dark colored squares did not meet the criteria used by the algorithm to positively identify them as nuclear particle generated tracks. These objects are either defects or scratches in the plastic, dust, or overlapping tracks (the algorithm ignores overlapping nuclear particle generated tracks).

The spatial distribution of positively identified tracks for the front and back surfaces of detector 10-5 are shown in Figures 4c and 4d, respectively. The automatic scanner ignores areas where there is a high density of overlapping tracks. This is illustrated in the mapping of the tracks shown in Figure 4c. In the photograph shown in Figure 4b, three cloudy areas are circled. Microscopic examination of these areas showed numerous overlapping tracks. The track density was too high for the scanner to accurately measure the contrast and size of the individual tracks. This is why no tracks have been identified by the scanner in these cloudy areas. On the backside of the detector, the identified tracks are not clearly associated with any of the wires. However, the density of tracks is greatest between the second and third wires. Looking at the photograph in Figure 4a, it appears that the density of the Pd deposit is greater between wires 2 and 3.

Figure 6 summarizes the scanned results obtained for a blank CR-39 detector. Both the front and back surfaces of the detector were scanned. For the blank detector, 147 tracks were observed on the front surface and 166 tracks on the back, for an average track density of $78 \text{ tracks cm}^{-2}$. The size distributions of the front and back surfaces of the blank detector are shown in Figures 6a and 6c, respectively. For both surfaces, there is a distribution of tracks between 1 and 5 μm in diameter and a second distribution between 6 and 40 μm in diameter. As discussed *vide supra*, the 60 μm thick polyethylene film on the detector will block 7 MeV alphas and 1.8 MeV protons. The tracks in the 1-5 μm range are likely due to very energetic protons with an estimated energy $\geq 10 \text{ MeV}$. Protons with this energy will be able to pass through the polyethylene film and would leave a small diameter track in the CR-39 detector. Oda et al. [64] did sequential etching of CR-39 exposed to 10 MeV protons. The track diameters were 1.0 and 2.6 μm after removing 6.5 and 15 μm of plastic, respectively. It is unlikely that the tracks in the 6-40 μm size range are due to alpha particles given that the polyethylene film blocks alphas with energies $\leq 7 \text{ MeV}$. These tracks are most likely recoils resulting from cosmic ray spallation neutrons interactions with the constituents of the detector, i.e. proton, carbon, and oxygen atoms. Nakamura *et al.* [65] have

observed thermal, 1-6 MeV, and 100 MeV neutrons in the spectrum obtained for cosmic ray spallation neutrons. CR-39 detectors will not respond to thermal neutrons. Neutrons that are 1-6 MeV in energy will cause proton recoils that will produce tracks with sizes ranging between 5 and 30 μm in diameter [34]. Neutrons with energies greater than 8 MeV will cause proton, carbon, and oxygen recoils that will produce tracks in CR-39 with major axis $\geq 30 \mu\text{m}$ [66]. Plots of minor vs. major axis of the tracks observed on the front and back surfaces are shown in Figures 6b and 6d, respectively. The plots show that the majority of the tracks exhibit ellipticity indicating that the particles have entered the detector at angles less than 90° .

Figure 7 summarizes the scans of the front and back surfaces of the CR-39 detector 10-5 used in the SRI replication. The size distributions of tracks on the front and back surfaces of the detector are shown in Figures 7a and 7c, respectively. The number of tracks on the front and back surfaces are significantly greater than what is observed on the blank detector. On the front surface, 34,254 tracks were positively identified. Two size distributions are observed: 0 to 3.5 μm and 3.5 to 20 μm in diameter. As can be seen in Figure 7a, the majority of the tracks ($\sim 70\%$) fall in the 0-3.5 μm size range. For the tracks in the 3.5-20 μm size range, the peak maximum occurs at 6.7 μm . A plot of minor vs. major axis of the tracks on the front surface is shown in Figure 7b. The line along the diagonal, where the minor and major axis are equal, represents particles that have entered the detector at a 90° angle. The majority of the tracks fall in the circled area. In this region, the major axis is larger than the minor axis indicating that these particles entered the detector at oblique angles. On the back surface, 750 tracks were identified by the scanner. Approximately 40% of those tracks fall in the 0-3.5 μm size distribution. The remainder of the tracks fall in the 3.5-40 μm size range with the peak maximum occurring at 8.8 μm . Figure 7d shows the plot of minor vs. major axis for the tracks identified on the back surface. The majority of the tracks fall in the circled region. Compared to the front surface, the tracks on the back surface exhibit greater ellipticity indicating that the angles of incidence are more acute.

Figure 8 summarizes the scans of the front and back surfaces of the CR-39 detector 10-6 used in the SRI replication. The results are similar to those observed for detector 10-5. Specifically there were significantly more tracks observed on the front surface than on the back surface. There are two populations of tracks on the front surface at 0-3.5 μm and 3.5-20 μm in diameter

and that the majority of the tracks fall in the 0-3.5 μm size range. Likewise there are two populations of tracks on the back surface at 0-3.5 μm and 3.5-40 μm in diameter. Again the majority of the tracks fall in the at 0-3.5 μm size distribution. For both detectors, the average number of tracks that do not overlap (front and back) is 10406 tracks cm^2 . The actual number of tracks cm^2 is greater than this as the scanner ignores regions where there is a high density of tracks. But an average track density of 10406 tracks cm^2 is still greater than background by a factor of 133.4.

From the scanned data, the flux of energetic particles can be estimated. The total number of positively identified particle tracks on the front surfaces of both detectors is 81667. Approximately 60% of the detectors are covered with the Pd deposit, Figure 4a. The total area of deposit in contact with the front sides of both detectors is therefore 2.4 cm^2 . Because CR-39 is an example of a constantly integrating detector, it is not known when the energetic particles were produced. However, it is assumed that the emission of energetic particles occurred after the Pd had plated out at which time the current was ramped up. This encompassed a six day period. Consequently the average flux, in 2π , is estimated to be 0.42 particles $\text{cm}^{-2}\text{s}^{-1}$. It should be noted that this average flux is the lower limit value as the scanner undercounts the number of tracks especially in high density areas where there is significant overlap between tracks.

3.3 LET Analysis of CR-39 Detectors 10-5 and 10-6

The scanned data obtained for detectors 10-5 and 10-6 were subjected to LET analysis to identify the charged particles that generated the tracks [59-61]. In this analysis, the scanned surfaces are “cathode” - the CR-39 surface closest to the cathode and “obverse” - side away from the cathode. The scanned area is $2.7 \times 10^{-3} \text{ cm}^2$ and the LET bin width is 0.25 keV/ μm CR-39. The work conducted in DIAS, NASA-JSC and NSSC has shown that background tracks are mainly due to radon alpha particles and are nearly the same. Therefore, since the background tracks are several orders of magnitude lower in number than the LENR-generated particle tracks, they can be ignored. From their LET characteristics, the LENR-generated particles detected with CR-39 detectors are mainly identified as protons and α particles. Neutrons produce proton recoils whose tracks have the same quality as proton and alpha particle generated nuclear tracks.

Consequently, the LET analysis cannot differentiate between tracks caused by neutrons and alphas/protons.

Figures 9(a) and (b) show the LET spectra of differential fluence for the detected charged particles. In the figures, particles with $LET \leq 31.0 \text{ keV}/\mu\text{m CR-39}$ are protons and particles with $LET \geq 31.0 \text{ keV}/\mu\text{m CR-39}$ are α particles. The LET criterion, maximum LET value for protons, can be determined by the particles minimum range, *i.e.*, the bulk etch value of CR-39 detectors. Figures 9(a) and (b) indicate that the LET values of protons and α particles measured with CR-39 detectors is from ~ 3 to $\sim 150 \text{ keV}/\mu\text{m CR-39}$; the LET spectrum for protons has several peaks, the major peak is at $\sim 3.25 - 3.50 \text{ keV}/\mu\text{m CR-39}$.

The number of charged particles observed are summarized in Table 1. Results in the table indicate that: (a) for the cathode surface of CR-39 detectors, events ($A = 1, 2$) are $\sim 96.3 \%$ of total events and events ($A \geq 3$) are $\sim 3.7\%$ of total; (b) for the obverse surface of CR-39 detectors, events ($A = 1, 2$) are $\sim 86.4\%$ of total and particles ($A \geq 3$) are 13.6% of total. Particles that are $A \geq 3$ are target fragments of CR-39 nuclei.

In the SRI immersion experiments, a $60 \mu\text{m}$ thick polyethylene film separated the detector from the cathode. The $\sim 60 \mu\text{m}$ polyethylene film between the cathode of the Pd/D system and the surface of CR-39 detector causes charged particles to lose $\sim 2 \text{ MeV/nucleon}$. Therefore, a proton requires an energy $> 1.8 \text{ MeV}$ to transit the film and an alpha will need $> 7 \text{ MeV}$. This fact tells us that α particles observed in CR-39 detectors are secondary particles produced by very fast primary protons and neutrons. Therefore the total energy for protons observed should be the energy observed plus the minimum energy and the total energy for α particles is the same as those observed.

For the data observed on CR-39 obverse surfaces (side opposite the cathode), the energy absorption in CR-39 should be considered. The minimum energy to pass through the $\sim 1 \text{ mm}$ thickness of CR-39 is $\sim 10 \text{ MeV}$ for protons and $\sim 40 \text{ MeV}$ for α particles. Protons with energies greater than 10 MeV can reach the obverse surface, but they need to be nearly perpendicular to the surface. The particles identified as alphas by the LET analysis are likely due to secondary

recoil particles whose tracks are similar to those created by 2-15 MeV alpha particles. Therefore the majority of tracks observed on the obverse surfaces must be due to secondary particles, *i.e.*, recoils. The energies reported in Figure 10(b) are measured energies, *i.e.*, without the minimum energy correction. Figures 10(a) and (b) show the energy distribution of particles produced by the Pd/D system and measured with CR-39 detectors. The major proton peak is at $\sim 11.5 - 12$ MeV for the cathode CR-39 surfaces and ~ 9.75 MeV for the obverse CR-39 surfaces. The distribution of α particles is nearly uniform because they consist of either secondary particles or neutron recoils.

From the LET analysis, the number of protons and alphas of a given energy is known. This information is summarized in Figure 10. Using these data, the total energy released by the LENR-generated particles can be estimated. For detectors 10-5 and 10-6 used in the SRI LENR experiments, the calculated energies for the measured protons and α particles are summarized in Table 2. The particles emitted by the cathode will travel in all directions. These particles will be produced throughout the thickness of the Pd deposit. Not all of these particles will reach the CR-39 detector. Consequently, the particle tracks that were scanned and analyzed are only some of the total particles generated in the LENR processes occurring inside the Pd lattice. In addition, some of the detected charged particles are produced through the interactions between neutrons and CR-39 material. Since the detection efficiency of CR-39 detectors for neutrons with energies from ~ 1 MeV to 20 MeV is $\sim 10^{-4}$ to 10^{-3} [49, 67, 68], the actual number of particles that entered the CR-39 detector should be higher than the number showed in Figure 10. Taking into account the poor neutron efficiency of CR-39 and the fact that not all particles, charged and neutral, will reach the detector, the actual total energy released by all the LENR-generated particles with high LET should be higher than that contributed by the observed particles.

4.0 CONCLUSIONS

In this communication, the results of microscopic examination, scanning, and LET analysis of CR-39 detectors used in Pd/D co-deposition experiments were discussed. In these experiments, a 60 μm thick polyethylene film separated the detector from the cathode. This film protected the detector from mechanical and chemical damage. It was shown that tracks, significantly above background, were observed on the front and back surfaces of the detector.

The tracks were dark, either circular or elliptical in shape, and exhibited bright centers when focusing deeper in the plastic. These properties are consistent with those observed for nuclear generated tracks. On the front surface of the detectors, the tracks correlated with the placement of the Ag wires. Based upon microscopic examination of the tracks; the size distributions and plots of major vs minor axis obtained from the scanner; and LET analysis, taking into account the 60 μm thick polyethylene film between the cathodes and the detector, the tracks on the front surface were tentatively identified as due to ≥ 1.8 MeV protons, ≥ 7 MeV alphas, and secondary particles due to recoils from either energetic protons and/or neutrons. On the back surface of the detectors, the tracks are tentatively identified as ≥ 11.8 MeV protons and/or recoils from either energetic protons and/or neutrons.

The detector designated 10-5 was then subjected to additional examination using sequential etching to further elucidate the identity of the particles that generated the tracks in the CR-39 detector. The results of this analysis is discussed in part 2 of these communiqués. As will be seen, both analyses (LET spectrum and sequential etching) gave complementary results. The analyzed data support Fleischmann's conjecture that nuclear processes occur in the Fleischmann and Pons (F&P) experiment, and indirectly support the notion that excess heat in the F&P experiment is of a nuclear origin.

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The authors dedicate this communication to the memory of Dr. Andrei Lipson of the Russian Academy of Sciences who passed away in November 2009. He was involved in the sequential etching analysis of the detectors used in the SRI experiment.

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TABLES

Table 1: Events observed for different experiments and detector surfaces.

Detector	Surface	Number of Events, N ^a				Ratio (%)			
		N ₁ (A=1)	N ₂ (A=2)	N ₃ (A≥3)	N(Total)	N ₁ /N	N ₂ /N	N ₃ /N	(N ₁ +N ₂)/N
10-5	Cathode	26516	6307	1431	34254	77.4	18.4	4.2	95.8
	Obverse	448	198	104	750	59.7	26.4	13.9	86.1
10-6	Cathode	33815	12241	1357	47413	71.3	25.8	2.9	97.1
	Obverse	511	210	111	832	61.5	25.2	13.3	86.7

a. A is the mass of the particle.

Table 2: Energies carried by the observed particles with high LET.

Detector	Surface	Total Particle Energy, MeV			Ratio (%)	
		E ₁ (A=1) ^a	E ₂ (A=2) ^b	E = E ₁ + E ₂	E ₁ /E	E ₂ /E
10-5	Cathode	266279	50548	316827	84	16
	Obverse	3596	1388	4984	72	28
10-6	Cathode	327263	103823	431086	76	24
	Obverse	4090	1283	5373	76	24

a. $E_1 = \sum N_i E_i$ where N_i is the number of protons with energy E_i

b. $E_2 = \sum N_j E_j$ where N_j is the number of alphas with energy E_j

FIGURE CAPTIONS

Figure 1. (a) Schematic of the rectangular, butyrate electrochemical cell showing the orientation of the cell components and the magnets. (b) Schematic of the 0.25 mm diameter Ag wire cathode. The continuous, single-wire cathode runs vertically over the CR-39 detector (solid lines) and under the plastic support (dashed lines) through holes in the plastic support at the top and bottom. PE = polyethylene.

Figure 2. Photomicrographs obtained at 200x magnification for CR-39 detectors used in Pd/D co-deposition experiments (a) without and (b) with 60 μm polyethylene covers between the cathode and the detector. The time duration of both experiments was the same.

Figure 3. (a) Photomicrograph of the CR-39 detector 10-5 used in the SRI replication obtained at a magnification of 200x. (b) Photomicrograph obtained at 1000x for the area indicated in (a). The top image was taken with the microscope optics focused on the surface of the detector. The bottom image is an overlay of two images taken at different focusing depths (surface of the detector and the bottom of the tracks).

Figure 4. (a) Photograph (provided by F. Tanzella of SRI) of the surface of the detector 10-5 facing the cathode obtained at the end of the experiment. The polyethylene cover is on the surface of the detector. Arrows indicate the placement of the Ag wires, which are numbered. (b) Photograph (provided by F. Tanzella of SRI) of the detector 10-5 after it was etched. The five dots on the upper right hand corner were created by pushing a pin into the detector. These marks indicate which side of the detector was facing the cathode. Circled areas indicate a high density of tracks. Scanned results of the detector that shows the spatial distribution of tracks on the (c) front and (d) back surfaces of the detector.

Figure 5. Photomicrographs of the CR-39 detector 10-6 used in the SRI replication obtained using the automated scanning track analysis system operating at 200x. The field of view is 500 μm by 600 μm . (a) Image obtained with the optics focused on the surface of the detector. (b) Image obtained with the optics focused on the bottom of the pits. Images (c) and (d) summarize the results of the track analysis performed by the automated scanner. (c) The scanner has

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Figure 8. Scanned results obtained for the CR-39 detector 10-6 used in the SRI replication. Front surface (47,413 tracks): (a) size distribution and (b) plot of minor axis and major axis. Back surface (832 tracks): (c) size distribution and (d) plot of minor axis and major axis.

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Figure
Figure 1

Figure 2

(a)

(b)

Figure 3

(a)

(b)

Figure 4

Figure 5

(a)

(c)

(b)

(d)

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Microscopic Analysis

Scanning and LET Analysis Results