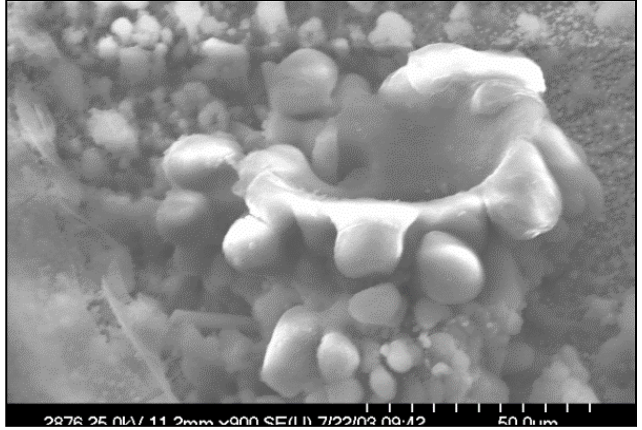
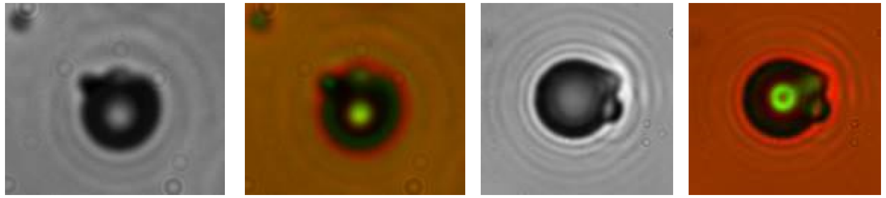


Pd/D Co-dep DT neutron

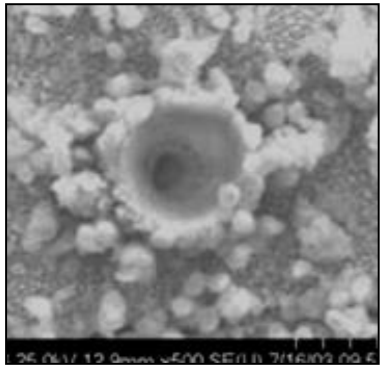


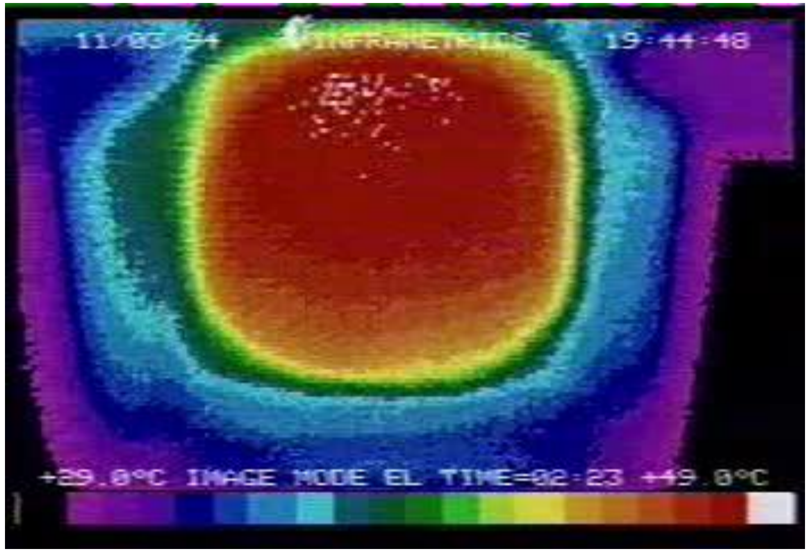
Pd/D Co-Deposition

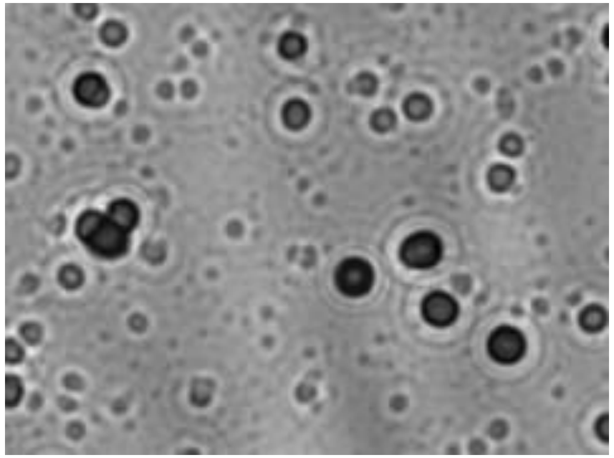
Pamela A. Mosier-Boss

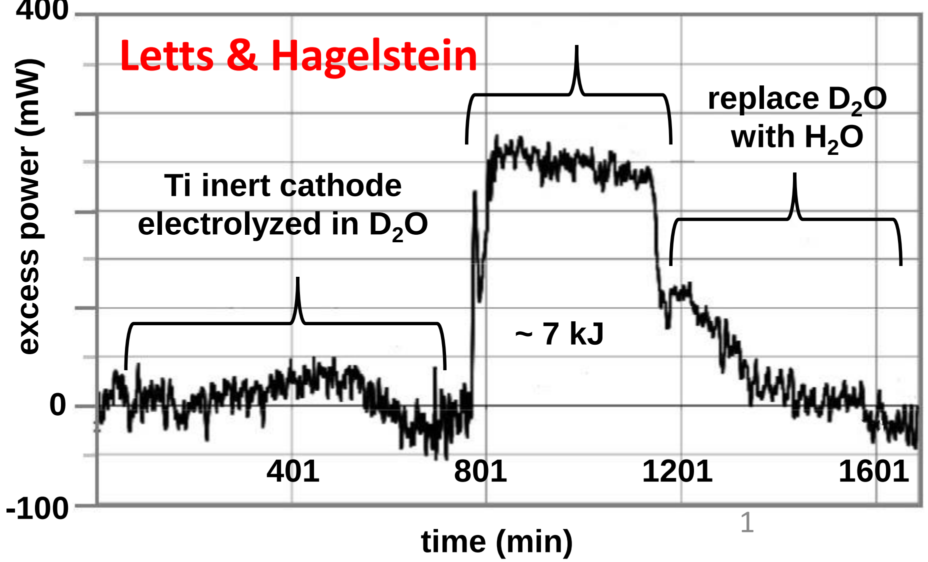
ARPA-E Workshop on Low-Energy Nuclear Reactions

October, 21–22, 2021



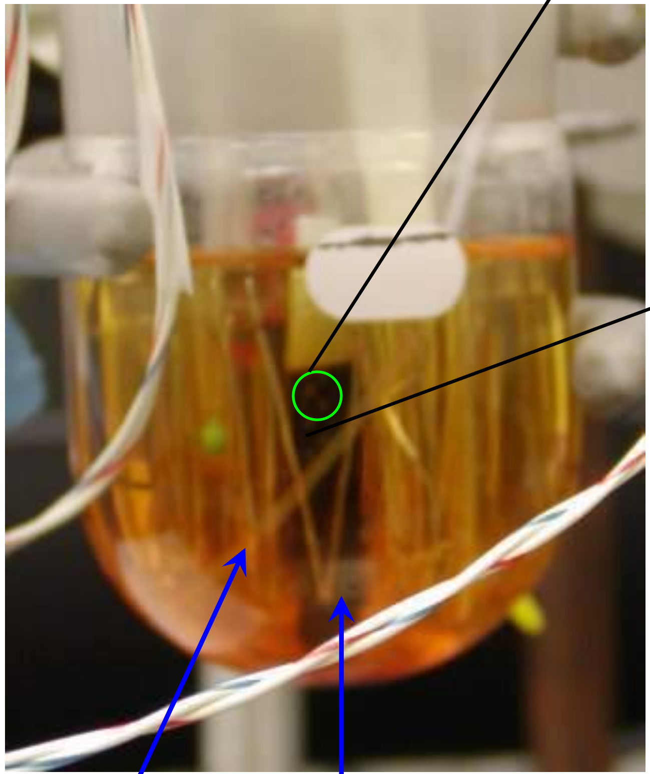




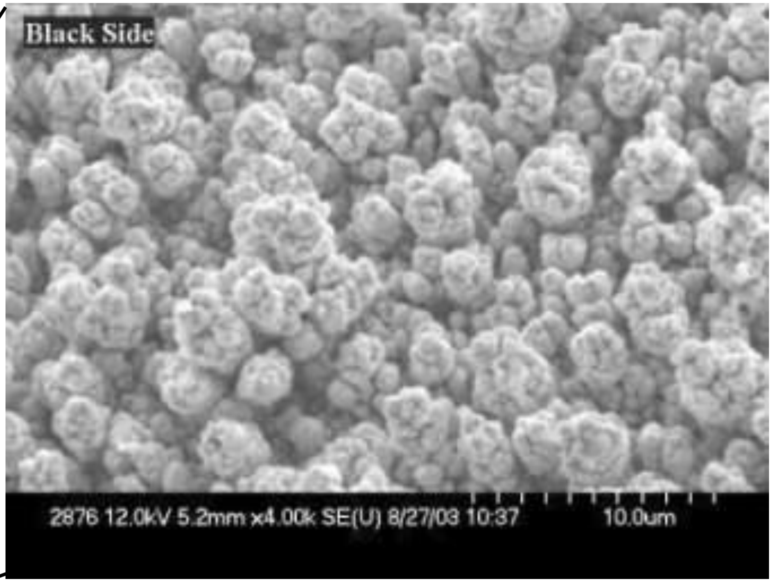


Description of Pd/D Co-deposition Experiment

Start off with a solution of $PdCl_2$ and LiCl in D_2O



Pt anode **Ni/Pd cathode**



P.A. Mosier-Boss, L.P. Forsley (2020) "Review of Pd/D co-deposition," in *Cold Fusion: Advances in Condensed Matter Nuclear Science*, ed. J.-P. Biberian, Elsevier Science Publishing Co. Inc., United States.

And references therein

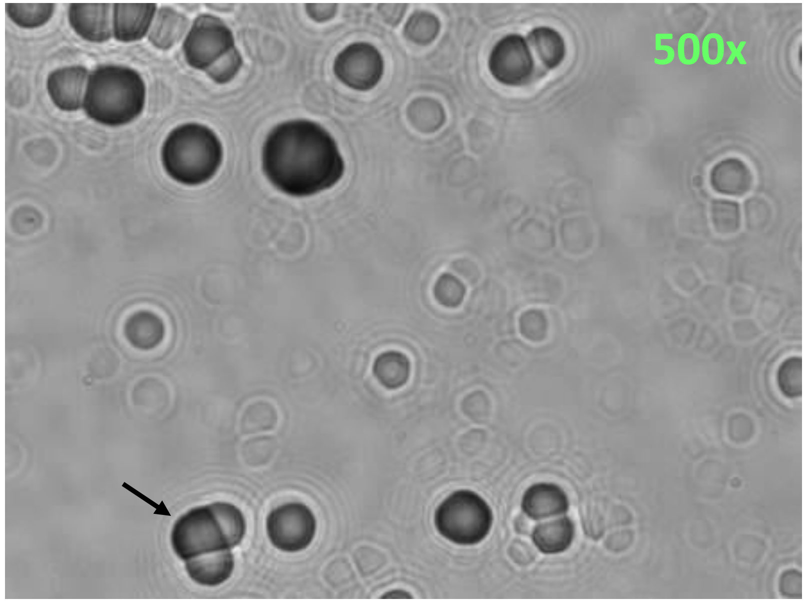
- **As current is applied, Pd is deposited on the cathode in the presence of evolving deuterium gas.**
- **The resulting deposit exhibits a highly expanded surface consisting of small spherical nodules (built in vacancies).**
- **Cyclic voltammetry and galvanostatic pulsing experiments indicate that, by using the co-deposition technique, a high degree of deuterium loading (with an atomic ratio D/Pd>1) is obtained within seconds. Szpak et al., J. Electroanal. Chem. 379 (1994) 121-127.**

Pd/D Co-deposition Results Obtained by Researchers

HEAT	TRITIUM	TRANSMUTATION	MeV PARTICLES	Radiation
Szpak et al.	Szpak et al.	Szpak et al.	Szpak et al.	Szpak et al.
Miles	Miles	Dash & Ambadkar	Tanzella et al.	Miles
Cravens & Letts	Bockris et al.	DeChairo et al.	NASA Glenn	
Letts & Hagelstein	Lee et al.		UCSD students	
DeChairo et al.				
Dash & Ambadkar				
Swartz				
Tanzella et al.				

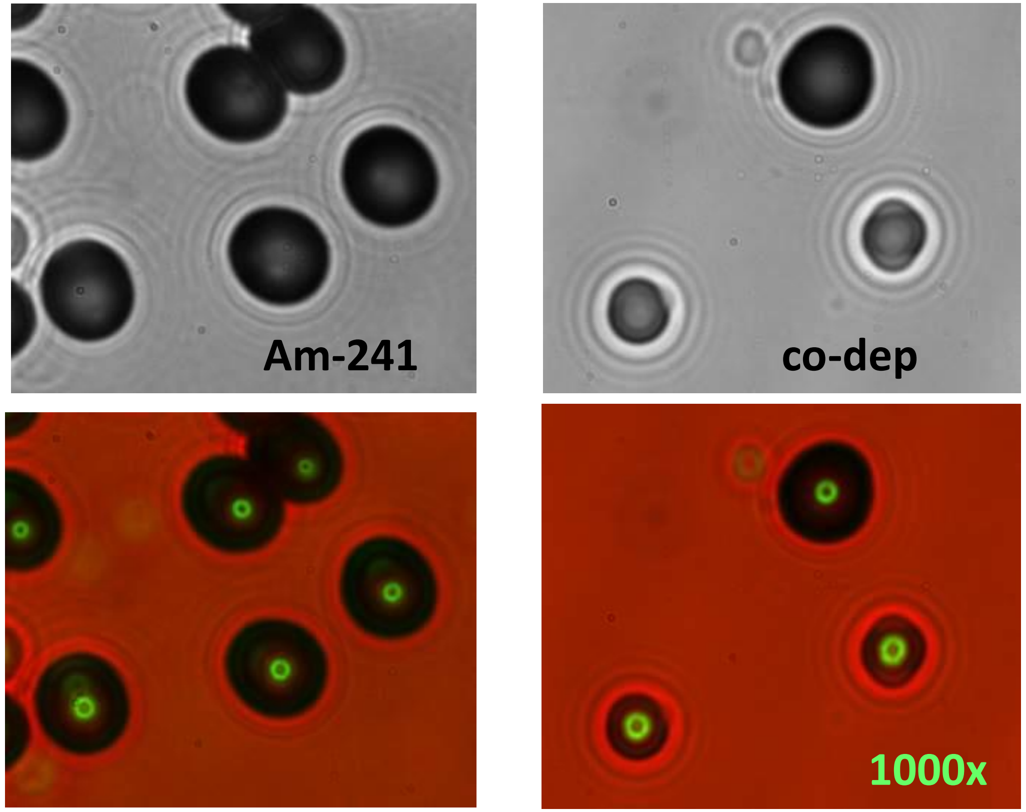
- Several researchers have, independently, used the Pd/D co-deposition technique
- The experiment is very flexible. Different calorimeters, plating solutions, and cell configurations have been used.
- Besides heat, the following nuclear emanations have been detected over a thirty year period of research: gamma/X-ray emissions, tritium production, transmutation, and energetic particle emissions.
- Pd/D co-deposition has proven to be a reliable means to generate LENR. It has also been repeatable and reproducible.
- The results of many of these experiments have been published in peer-reviewed journals.

Detection of Energetic Particles using CR-39



- CR-39 detector is placed in contact with the cathode because high energy charged particles do not travel far through the Pd deposit and water layer
- Tracks correspond to the placement of the Pd deposit
- Arrow indicates a triple track caused when a 14.1 MeV neutron shatters a carbon atom into three alpha particles. Triple tracks are diagnostic of 14.1 MeV neutrons.
- Mylar spacer simulation experiments indicate that the majority of the particles have energies ≤ 1 MeV when they impact the detector. These conclusions are supported by computer modeling of the tracks using the TRACK_TEST code developed by Nikezic and Yu

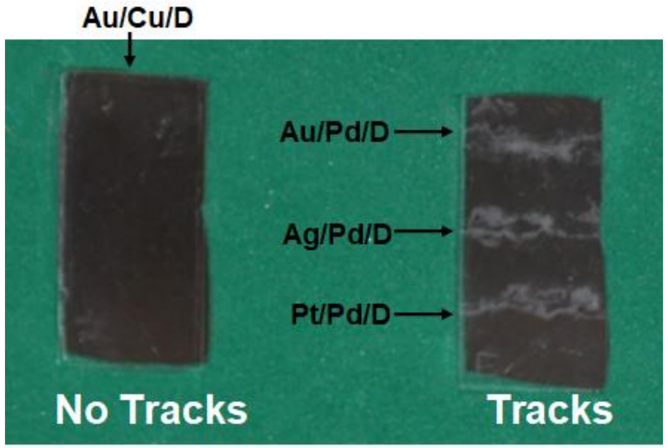
TOP: optics focused on the surface
Bottom: overlay of two images (surface and track endpoints)



Nuclear tracks are dark when focused on the surface. Focusing deeper inside shows bright points of light.

Summary of Control Experiments

EXPERIMENT	RESULTS OF CR-39
CR-39 placed in contact with cell, electrodes, and electrolyte components	No pits observed. Tracks are not due to radioactive contamination of the cell components
Electrolysis done in the absence of $PdCl_2$	No pits observed. Tracks not due to impingement of D_2 gas on the surface of the CR-39.
Pd/D co-deposition done in a two chamber cell to prevent mixing of D_2 and O_2 gases to prevent recombination.	Pits observed. Tracks are not due to D_2 and O_2 recombination.
Replace D_2O with H_2O	Tracks were observed with H_2O but the density was several orders of magnitude less than what was observed for D_2O.
Replace Pd/D co-deposition with Pd wire	Saw tracks when Pd wire was used tracks but the density of tracks is less than was observed for co-deposition. Distribution of tracks is not homogeneous.



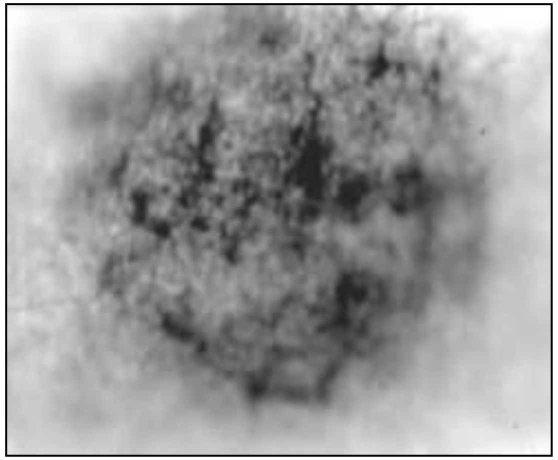
- Both Cu and Pd were plated out in the presence of deuterium gas
- Both Cu and Pd metal deposits were dendritic
- During electrolysis of D_2O, OD^- ions form at both cathodes
- Only significant difference is that Pd absorbs D and Cu does not
- Tracks in CR-39 are not due to chemical attack of OD^- ions nor are they due to the metal dendrites piercing into the plastic
- Replacing Cu with Ni gave the same results

Note: CR-39 is etched between 60-85°C. Higher T deforms the detector and does not create track-like features.

Chemical/Mechanical/Thermal Attack?

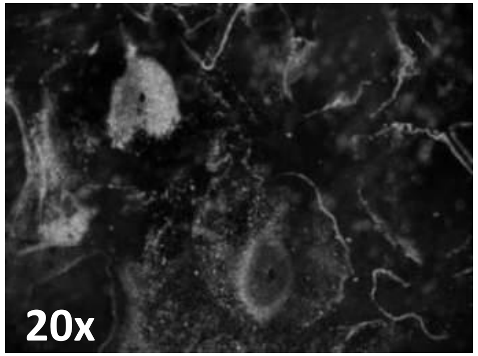
Ni/Pd-D, no external field (similar damage when CR-39 is exposed to a gamma/X-ray source)

photographic film Ag/Pd-D, Mylar separates cathode from film (emission of γ/X-rays)

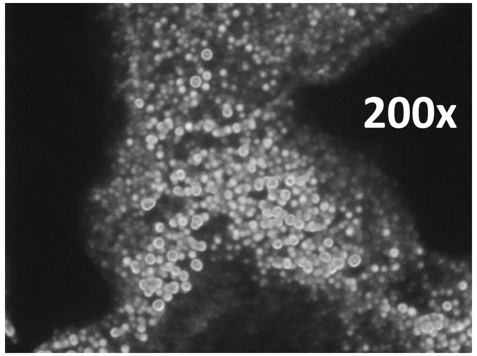


- For Ag, Au, or Pt wire cathodes, tracks were obtained in the CR-39 in both the presence and absence of an external E/B field. Pd/D co-deposition on Ni screen behaved differently.
  - In the absence of a field, no tracks were observed, just see the impression of the Ni screen. Tracks observed when either the experiment is conducted in the presence of an E/B field or when Au was first plated on the Ni screen prior to Pd/D co-deposition.
- These observations suggested an experiment to rule out chemical, mechanical, and thermal sources for the tracks
  - Use a composite cathode (Au was plated on half of the Ni screen). Perform the experiment in the <u>absence</u> of an external E/B field
  - Both halves of the cathode experience the same chemical/electrochemical environment at the same time
  - Provides evidence that the tracks are not due to chemical, thermal, or mechanical damage

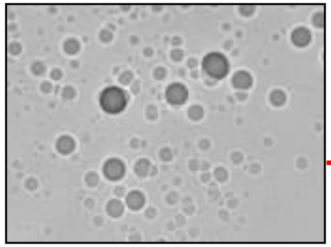
Ni/Pd-D, external B field



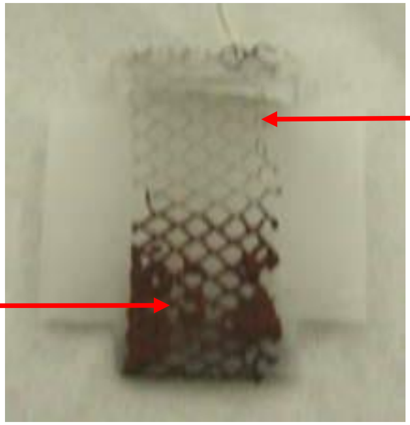
Ni/Au/Pd-D, no external E/B field

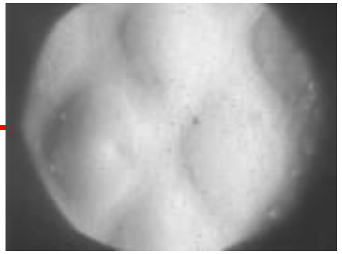


tracks on Ni/Au half



1000x





20x

no tracks on bare Ni half

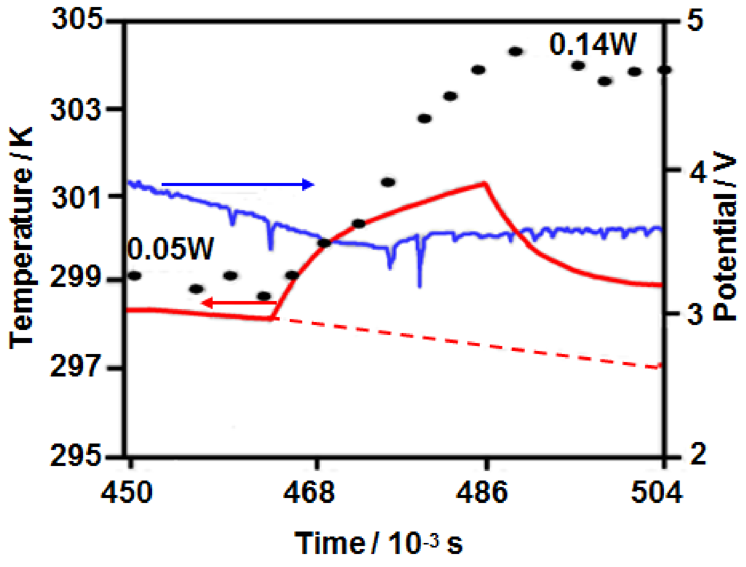
Assessment of Needs

- Pd/D co-deposition experiments have been piecemeal. Some scientists have focused on heat while others have looked for nuclear products. There have been very few experiments that have done both at the same time. In order to gain acceptance by the scientific community, both are needed.
- A Pd/D co-deposition experiment is proposed that does both calorimetry and nuclear diagnostics (both real time and integrating). **Such an approach can be used to test other cathodes (e.g. other sources of bulk Pd and Pd alloys with B, Ce, and Ag)**. The nuclear nature of the phenomenon must be understood before scale up can be done to make a practical energy source.
  - Need a sensitive calorimeter (precision ≤ 1%, sensitivity ≤ 10 mW) that uses a closed cell. Cell should be designed to measure gas for ^4He during the experiment when heat production occurs. This will require a mass spectrometer capable of measuring ^4He in the presence of any unrecombined D_2 gas and a 0.1 ppb detection limit.
  - Material assays of cell and electrolyte components should be done before and after. This includes measurements of tritium and elemental analysis. Analysis of the cathode needs to be done when the experiment is completed. Isotopic composition of the elements needs to be determined. Equipment needed include ICP-MS, liquid scintillator, and SEM-EDX.
  - Nuclear diagnostics to monitor running cells and background. These include ≥30% HPGe detectors with Be window for γ/X-ray measurements down to 13 keV (Compton suppression improves S/N), neutron scintillation spectrometer, bubble detectors for neutrons, and CR-39. Appropriate shielding also needed.
  - Explore other diagnostics to detect LENR-generated products in real time that can be coupled to the cathode and immersed in electrolyte (e.g. YAP:Ce for charged particles, scintillation fiber optics for neutrons, thermoluminescent dosimeter for radiation, piezoelectrics for heat and pressure, …)
  - Explore means of triggering (important for control and enhancing the effect)

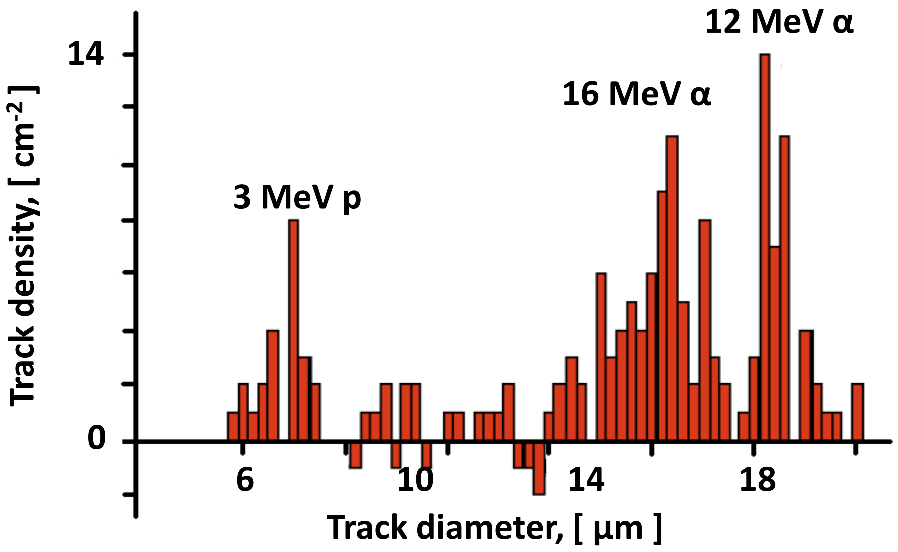
How Should Such a Program be Structured?

- The goals of a program are to gain acceptance of the phenomenon by the scientific community and to establish control for scaling which will lead to a practical LENR-based device
- A multidisciplinary approach is needed involving physicists, chemists, metallurgists, materials scientists, and engineers who are open-minded and can work together
- The program should engage scientists who have experience in conducting LENR experiments
  - Too many efforts have not built on what was done previously by others. This wastes time and resources.
- There should be open lines of communication between the various groups working on the effort
  - Too many multi-group efforts have prevented communication between the groups involved
- Results of the effort need to be published in peer-reviewed journals

BACKUPS



305
303
301
299
297
295
5
4
3
2
0.14W
0.05W
Temperature / K
Potential / V
450
468
486
504
Time / 10-3 s



12 MeV α
16 MeV α
3 MeV p
14
0
Track density, [cm-2]
6
10
14
18
Track diameter, [μm]

Summary of Pd/D Co-deposition Experiments

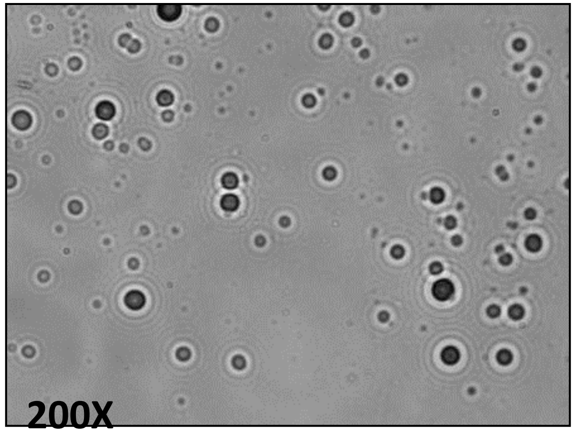
- **Szpak *et al.***: chloride complex of Pd; open cells; external E/B fields; measured heat (thermometry, IR imaging), tritium, γ/X-rays, transmutation, energetic charged particles, and neutrons. **KEY RESULTS: cathode is the heat source, detected triple tracks due to 14.1 MeV neutrons, production of tritium and γ/X-ray emissions were sporadic and occurred in bursts**
- **Miles**: ammonia complex of Pd; open cells; measured heat (isoperibolic calorimeter), tritium, and radiation. **KEY RESULTS: heat produced was comparable to that seen with bulk Pd, observed the positive feedback effect, heat could not be explained by shuttle reactions**
- **Cravens and Letts**: chloride complex with Pd; closed cells; explored means of stimulation (heat pulses, Rf, magnetic field, and laser); and chemical additives; measured heat (isoperibolic calorimeter) **KEY RESULTS: magnitude of heat production could be increased by the stimulation applied**
- **Letts and Hagelstein**: chloride complex with Pd; closed cells; magnetic fields; measured heat (Seebek calorimeter) **KEY RESULTS: slow co-dep produced no heat, fast co-dep did; ran an experiment that produced 20 kJ of excess heat when 10 kJ would have exceeded any known chemistry**
- **DeChairo *et al.***: chloride complex with Pd; open cells; magnetic fields; measured heat (Seebek calorimeter) and transmutation. **KEY RESULTS: transmutation products seen were dependent upon the orientation of magnetic field**
- **Dash and Ambadkar**: using Pd as the anode, plated Pd on Pt; closed cells; measured heat (Seebek envelope calorimeter) and transmutation. **KEY RESULT: deposit showed presence of Ag and Cd not originally present in the cell**

Summary of Pd/D Co-deposition Experiments (Cont.)

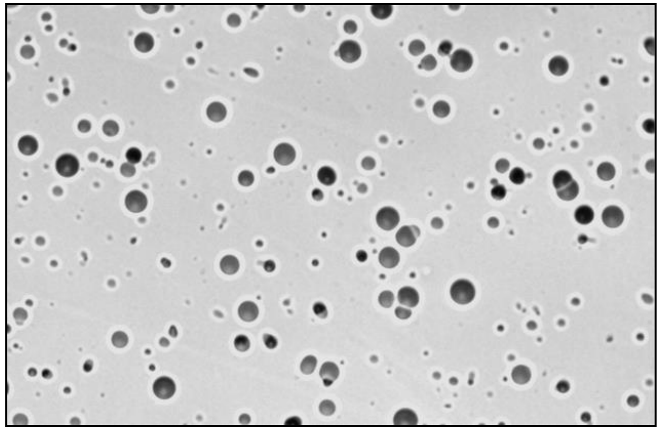
- **<u>Swartz</u>**: co-dep done on a spiral Pd cathode; open cells; measured heat (multiring thermal spectroscopy with joule controls)
- **<u>Tanzella *et al.*</u>**: co-deposited $PdH(D)_x$ on highly loaded stabilized $PdH(D)_x$ and $NiH(D)_x$ wires; open system; measured heat (exploding wires, cryogenic calorimeter)
- **<u>Bockris *et al.*</u>**: chloride complex with Pd; open cells; measured tritium in gas and electrolyte. **KEY RESULT: tritium produced when low tritiated D_2O was used but consumed when highly tritiated D_2O was used**
- **<u>Lee *et al.*</u>**: chloride and ethylenediamine complexes with Pd; closed system; measured tritium in electrolyte. **KEY RESULT: same as Bockris observed**
- **<u>Tanzella *et al.*</u>**: chloride complex with Pd; open cells, magnetic fields; measured energetic particles (used CR-39; detectors subjected to microscopic analysis, scanning with LET analysis, and sequential etching). **KEY RESULTS: detected 3 MeV p, 12 and 16 MeV α, and 2.5 MeV neutrons**
- **<u>NASA Glenn</u>**: chloride complex with Pd; open cells, magnetic fields; measured energetic particles (CR-39 and bubble detectors)
- **<u>UCSD Chemical Engineering students</u>**: chloride complex with Pd; open cells, magnetic fields; measured energetic particles (CR-39 detectors)

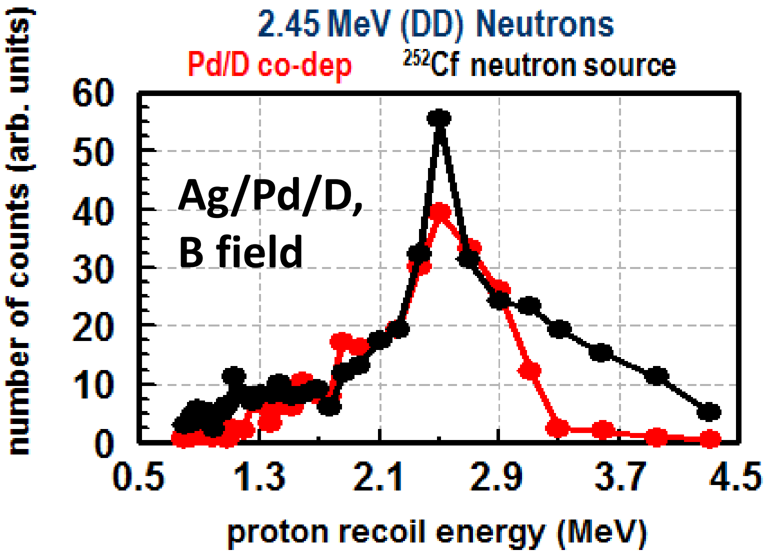
Pd/D Co-deposition: Evidence of Neutrons

Ag/Pd/D, B field



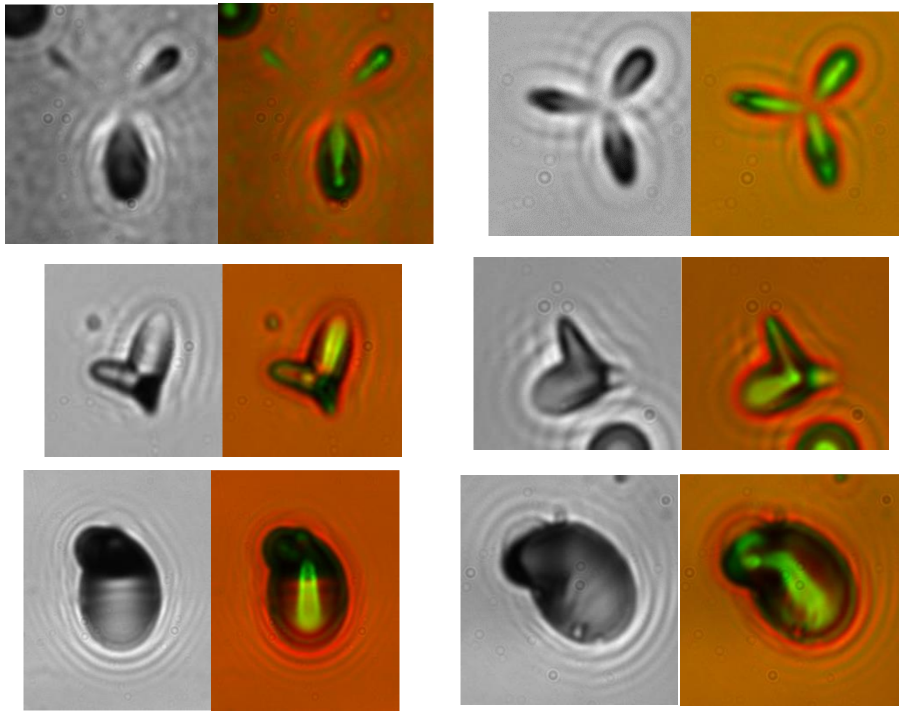
^{238}PuO neutron source





- Tracks have been observed on the backsides of the 1 mm thick CR-39 detectors used in co-dep.
- Only ≥ 43 MeV alphas, ≥ 10 MeV protons, or neutrons can go through the detector
- Neutrons can scatter producing recoil protons, carbons, or oxygen nuclei inside the CR-39
- Tracks on the backside are similar to those observed when a detector is exposed to a neutron source
- Sequential etching shows that 2.5 MeV neutrons are produced

Pd/D Co-dep DT Neutron



- Triple tracks are diagnostic of 14.1 MeV neutrons
- The n + ^{12}C reaction can proceed to the four-body final state through one or more of the following reaction mechanisms:

$n + {}^{12}C \rightarrow n' + \alpha + ({}^{8}Be \rightarrow 2\alpha)$

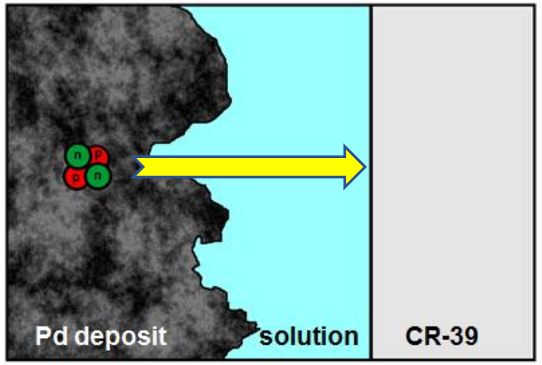
$n + {}^{12}C \rightarrow \alpha + ({}^{9}Be \rightarrow n' + ({}^{8}Be \rightarrow 2\alpha))$

$n + {}^{12}C \rightarrow \alpha + ({}^{9}Be \rightarrow \alpha + ({}^{5}He \rightarrow n' + \alpha))$

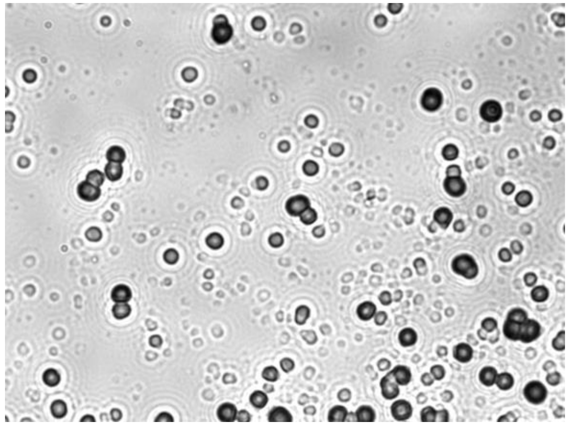
$n + {}^{12}C \rightarrow ({}^{8}Be \rightarrow 2\alpha) + ({}^{5}He \rightarrow n' + \alpha)$

$n + {}^{12}C \rightarrow n' + \alpha + \alpha + \alpha$

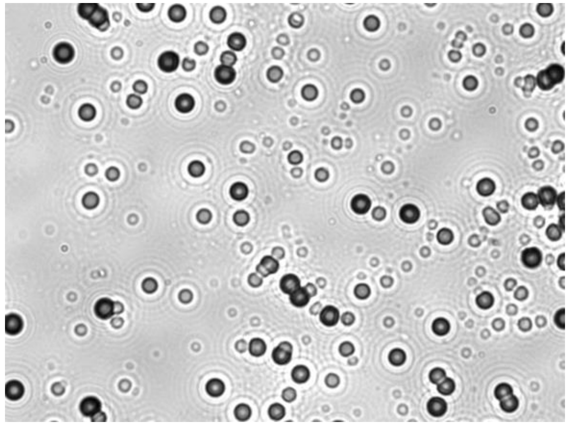
Energy of Charged Particles When They Impact the Detector



Pd/D Co-deposition, 500x

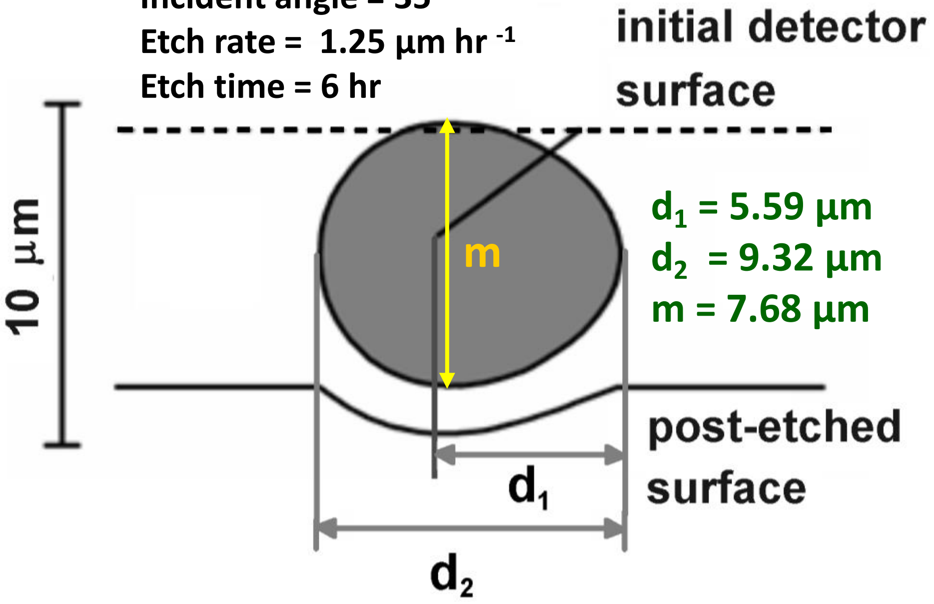


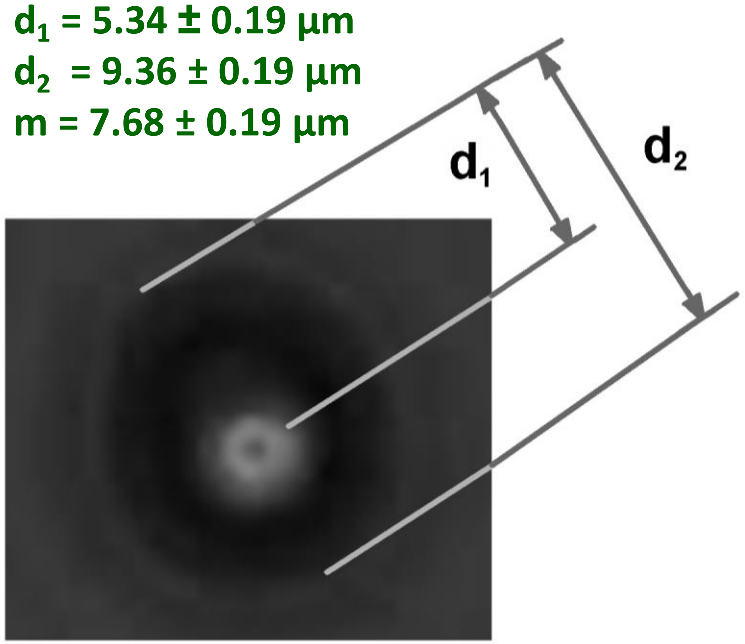
1 MeV alphas, 500x



Use of TRACK_TEST to Estimate Particle Energy

E_α = 1.3 MeV
Incident angle = 35°
Etch rate = 1.25 µm hr $^{-1}$
Etch time = 6 hr





- After it is born, a charged particle has to traverse through the Pd deposit and water layer before it impacts the CR-39 detector.
- To simulate the effect of water on the transmission of charged particles, layers of Mylar were placed between a CR-39 detector and an ^{241}Am alpha source. A comparison of Pd/D co-deposition tracks, with ~1 MeV alpha tracks, formed by placing 24 µm of Mylar between an ^{241}Am alpha source and a CR-39 detector, shows that the observed tracks are indistinguishable.
- The simulation indicates that the majority of the particles have energies ≤ 1 MeV when they impact the detector.
- This conclusion was supported by computer modeling of the tracks using the TRACK_TEST code developed by Nikezic and Yu