CR-39 Results Obtained Using Pd/D Co-deposition

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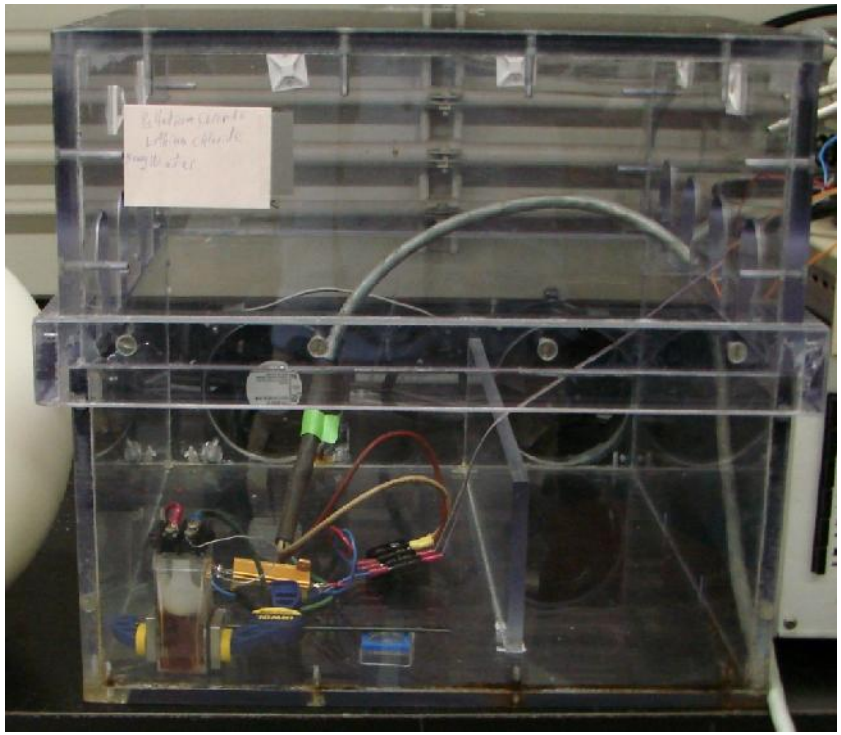
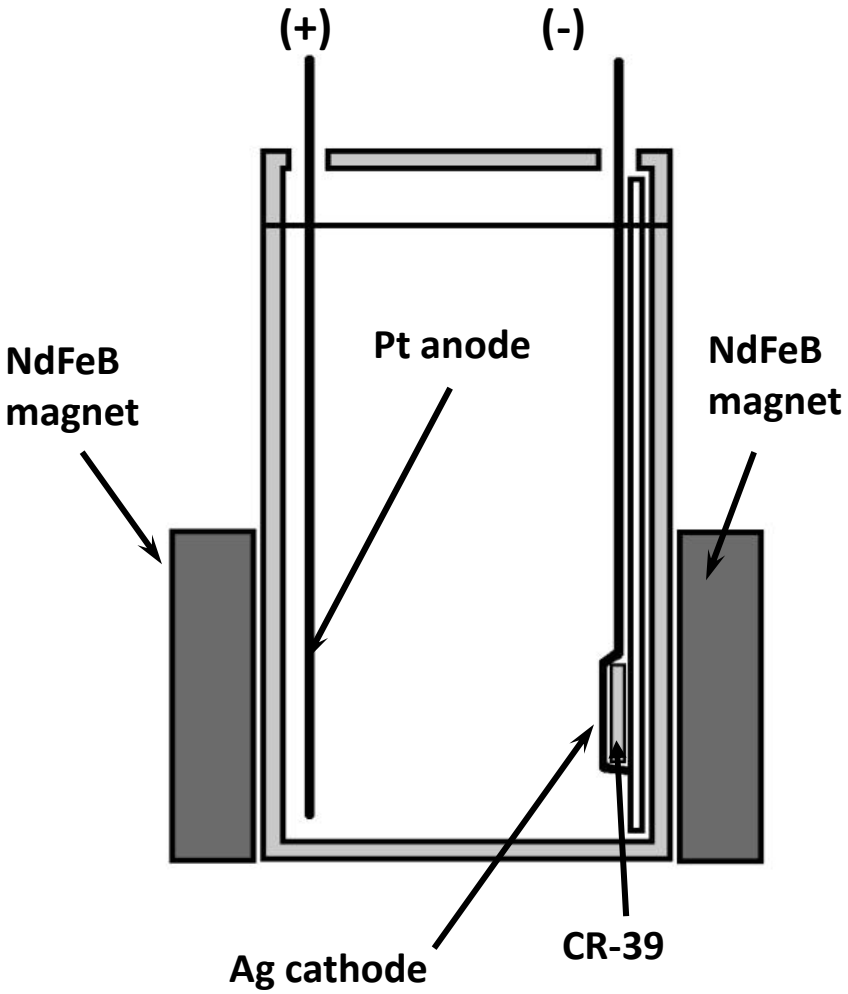
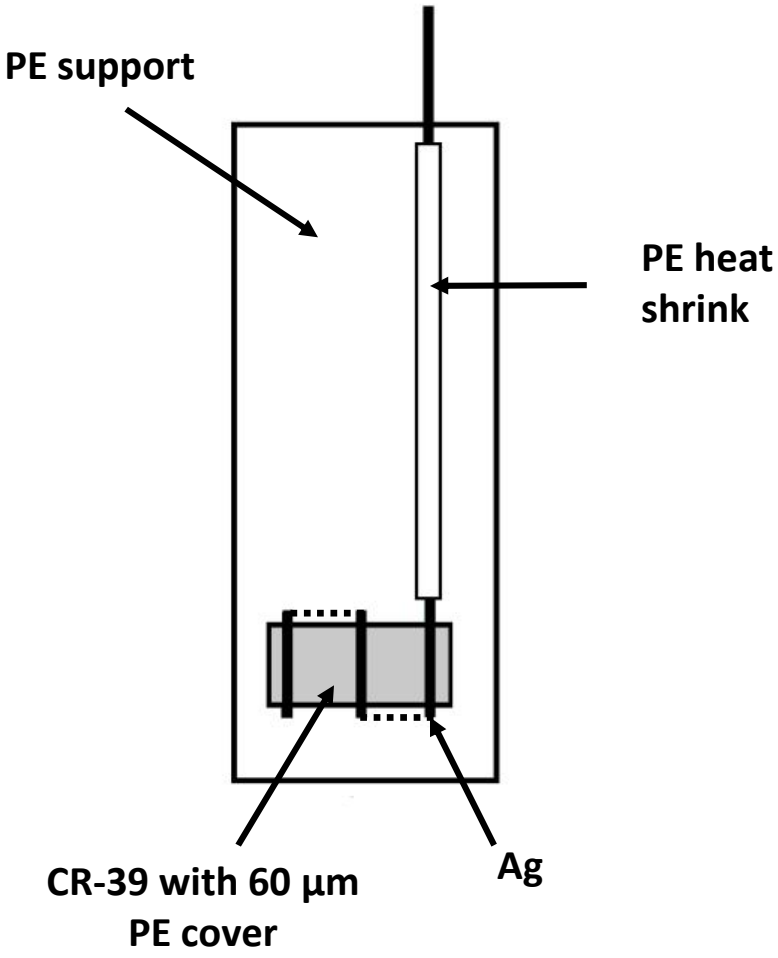
SRI Replication of CR-39 Results



Schematic of SRI Replication Cell



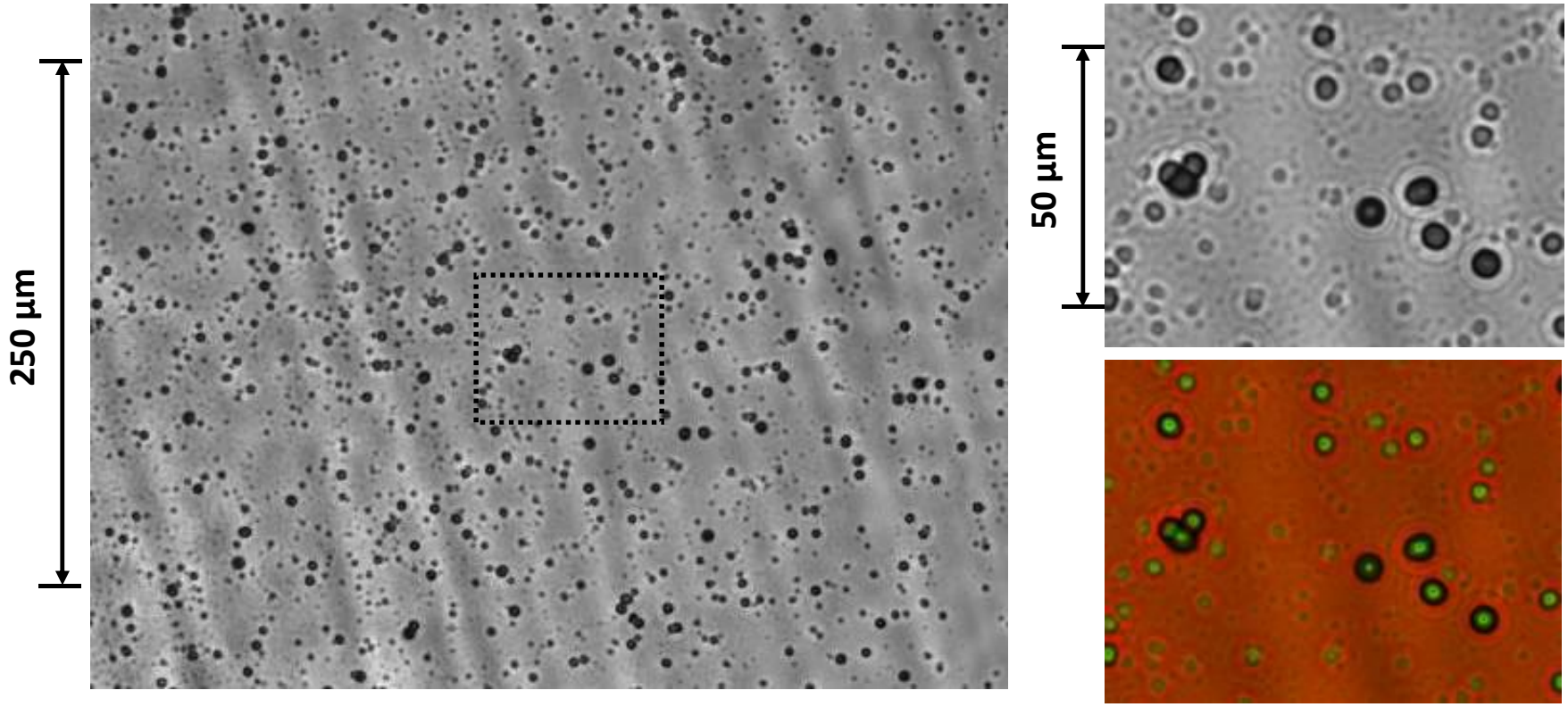


▼60 µm PE between CR-39 & Ag/Pd/D cathode

▼LET curves indicate that 60 µm PE will block 7 MeV alphas and 1.8 MeV protons

▼ The detector underwent microscopic examination, it was scanned, and sequentially etched

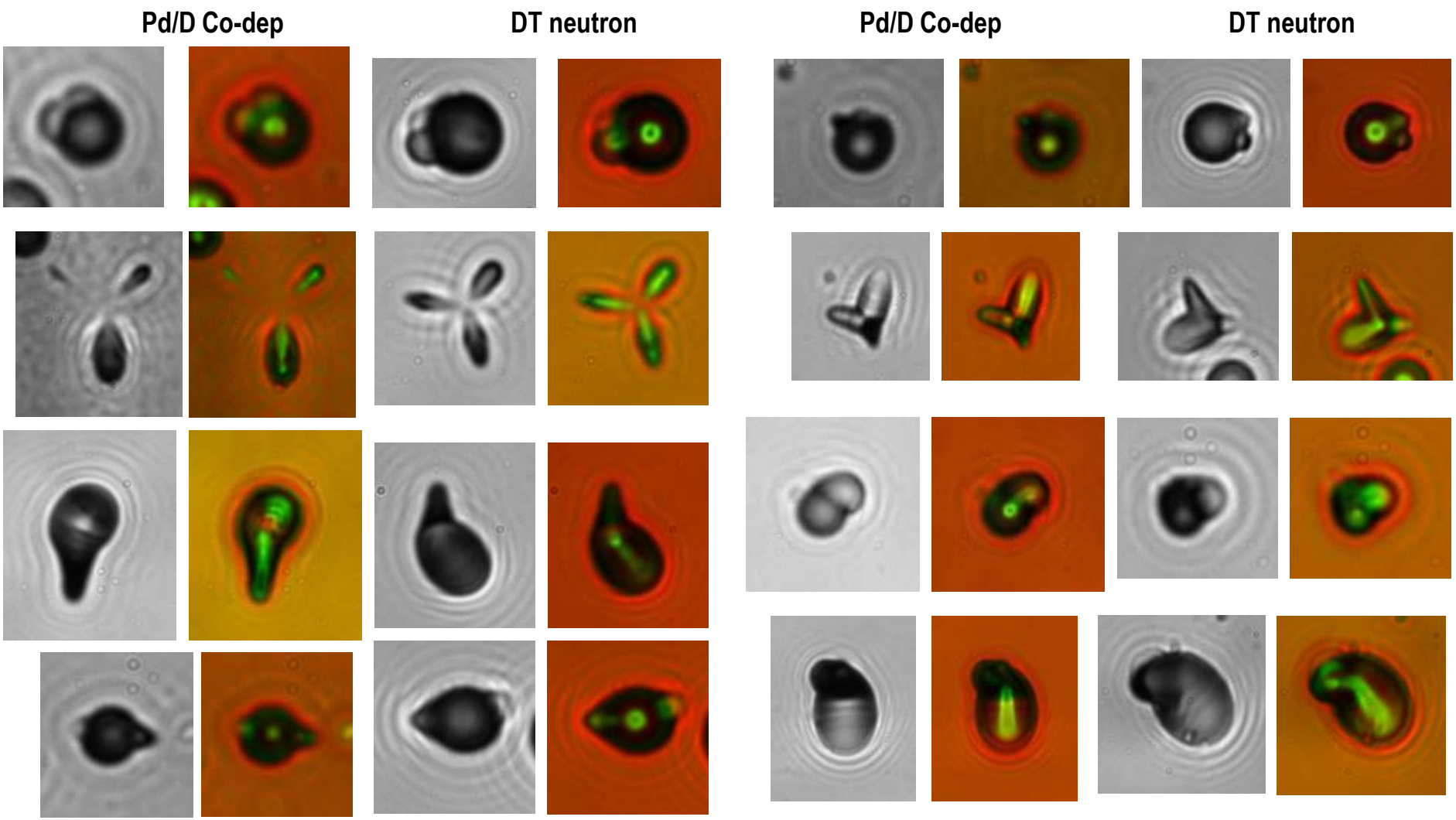
Microscopic Analysis SRI Detector



60 µm PE film between cathode and detector

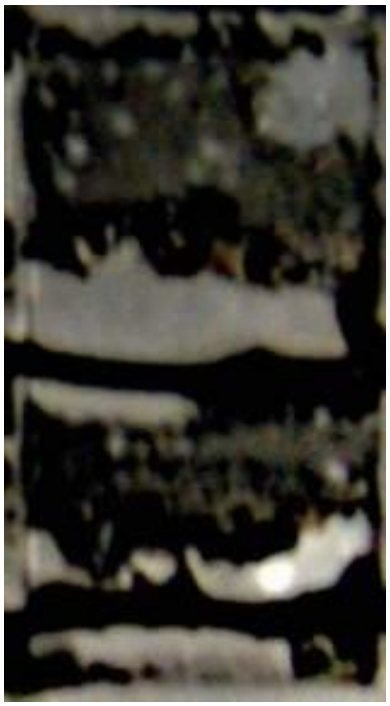
Two Triple Tracks were Observed on the SRI detectors: Evidence of > 9.6 MeV Neutrons

Johan Frenje, MIT, "I must say that the data and their analysis seem to suggest that energetic neutrons have been produced," (ACS, 2009)

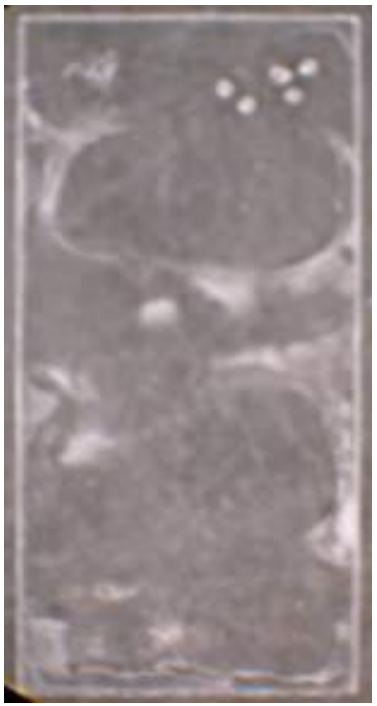


Spatial Distribution of Tracks

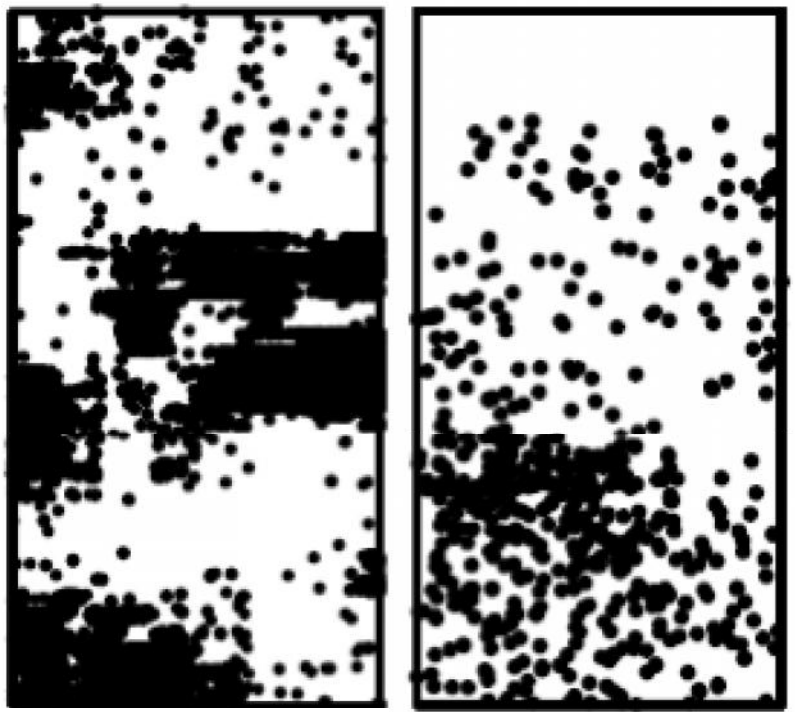
PE film



Etched CR-39



Scanned Results



FRONT BACK

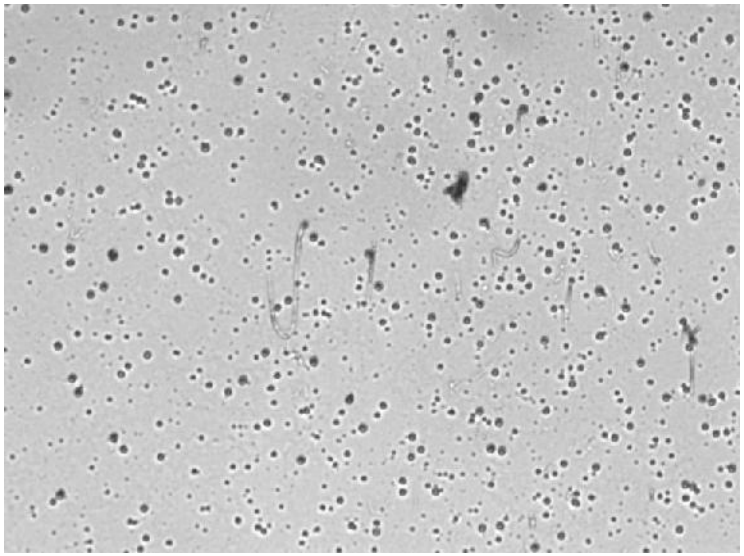
▼Ohmic measurements indicated that the Pd metal had not gone through the PE film

▼Tracks correlated with the Pd deposit

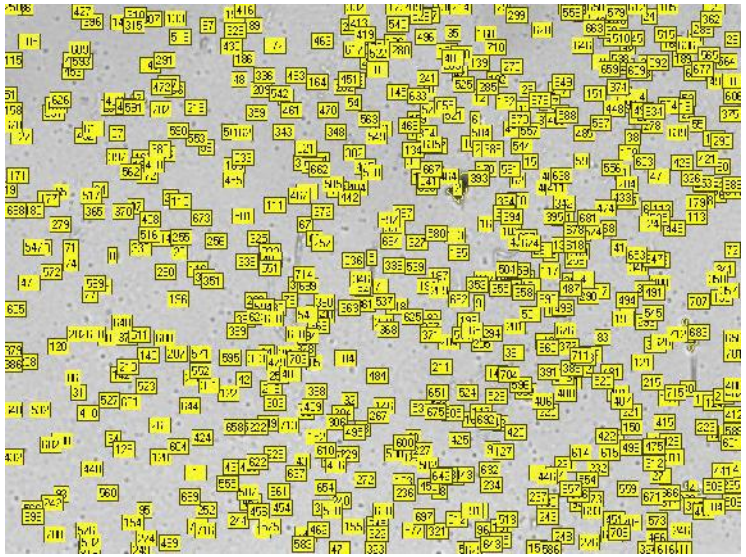
- Pd deposit is the source of the tracks

Example of a Scanned Image

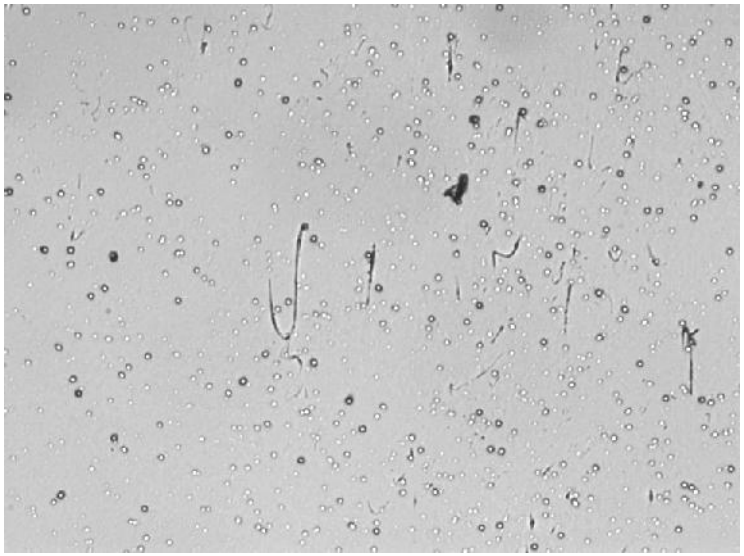
image



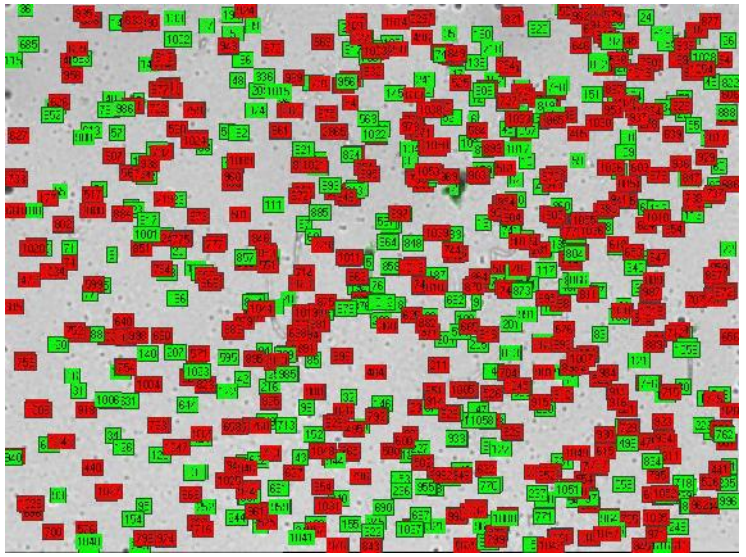
objects identified



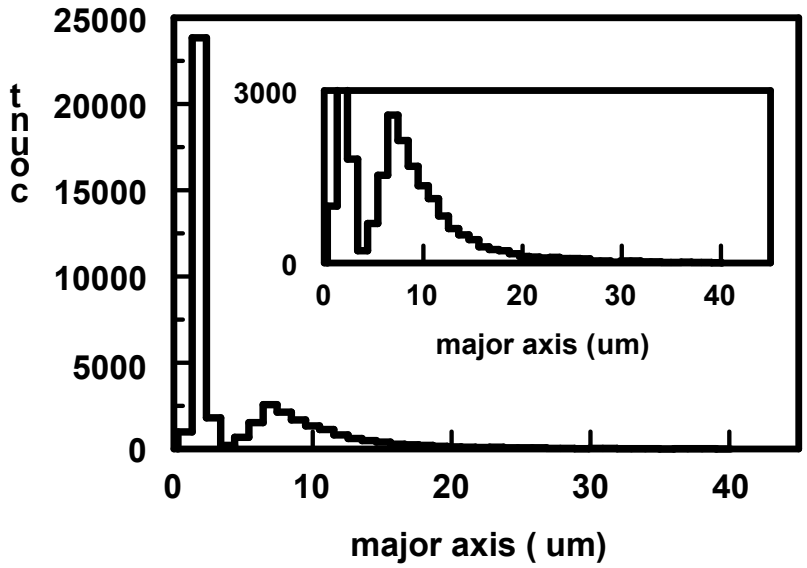
focus inside pits

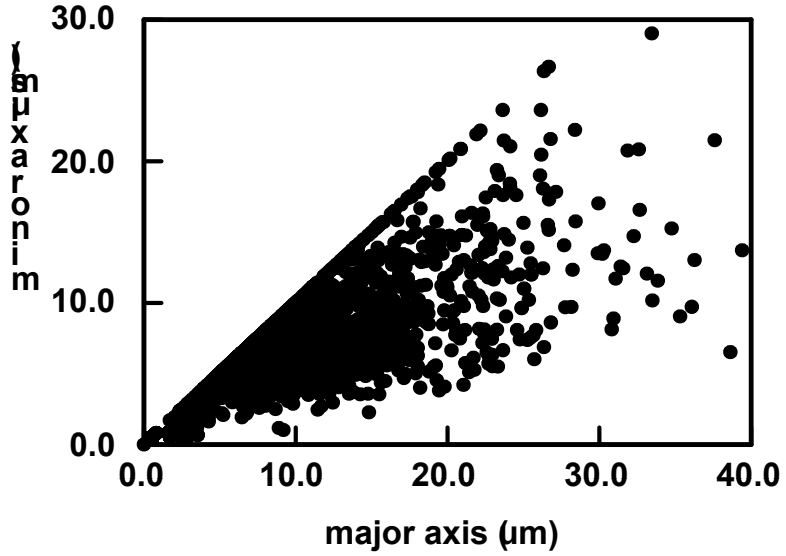


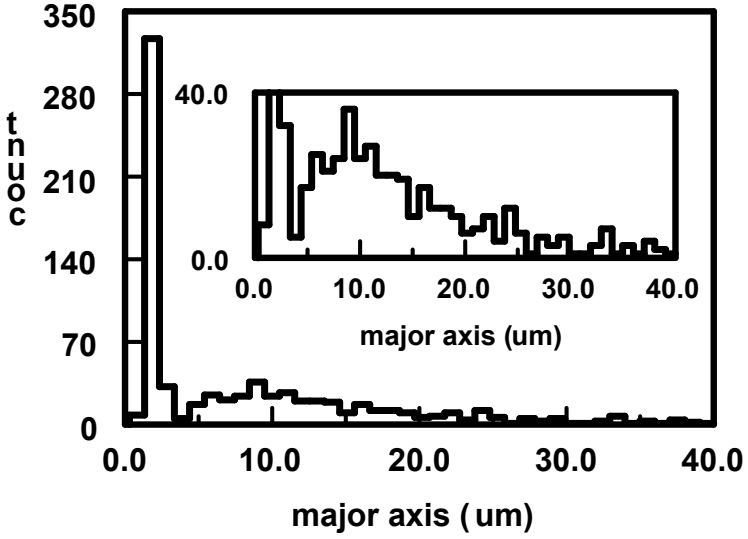
green = tracks

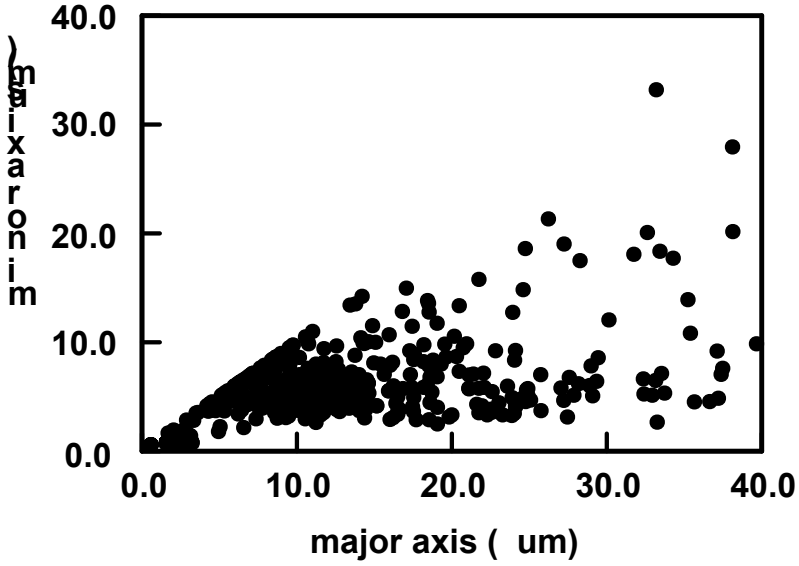


Automated Scanner Results Obtained for the CR-39 Detector used in the SRI Replication

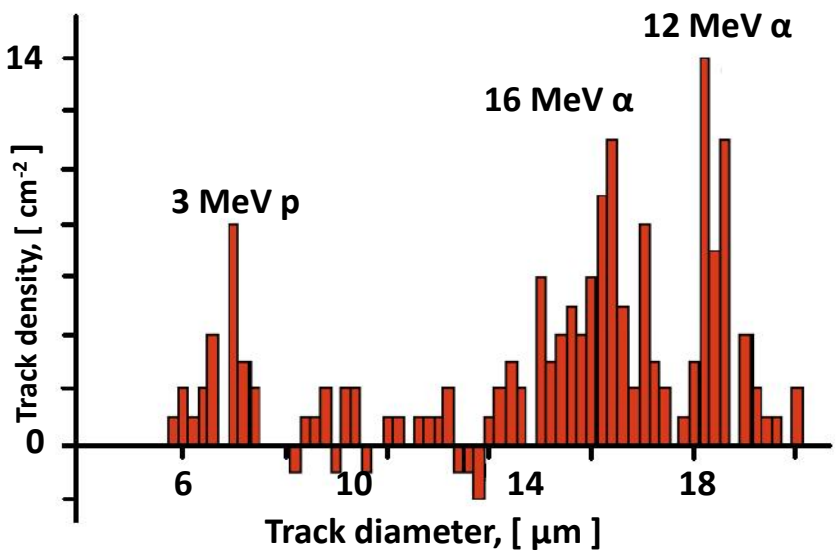




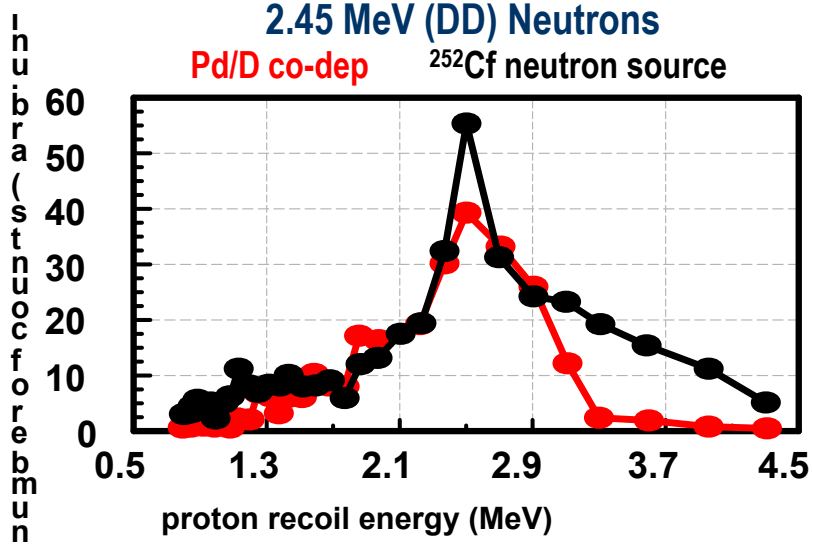




Sequential Etching Analysis (Lipson and Roussetski)

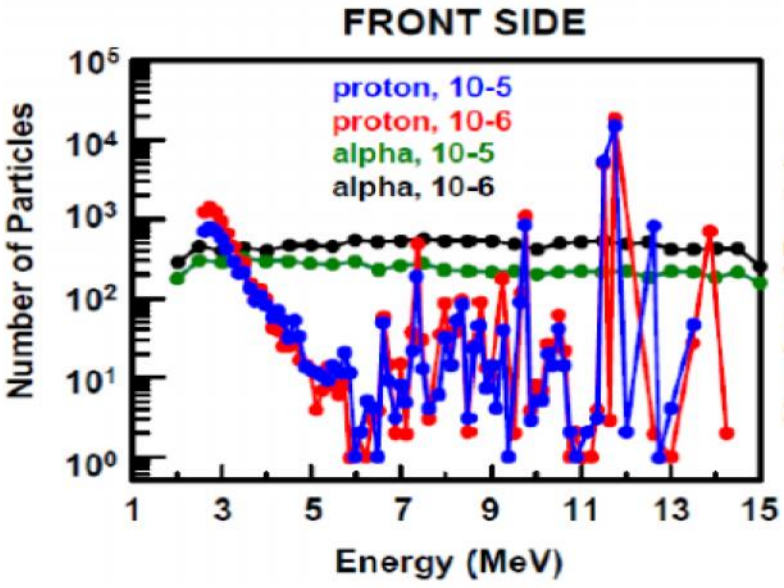


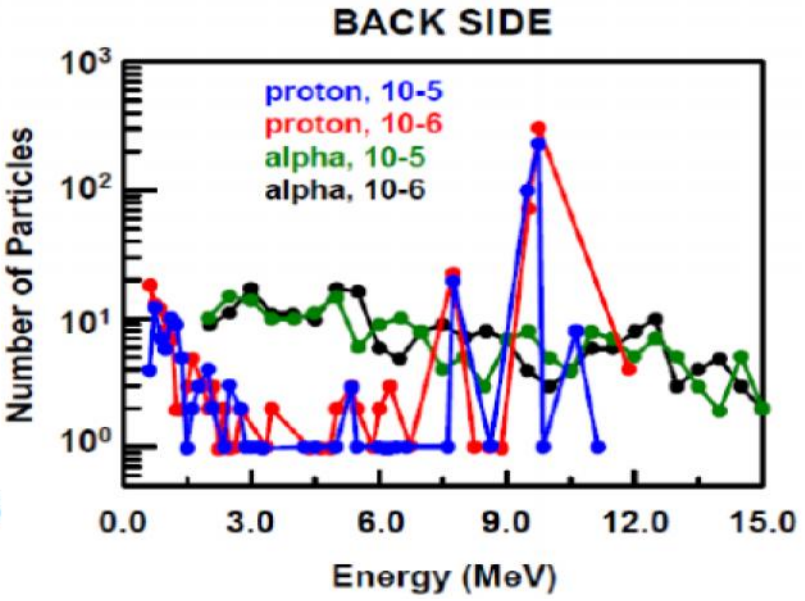
detector inside cell, 21 hour etch



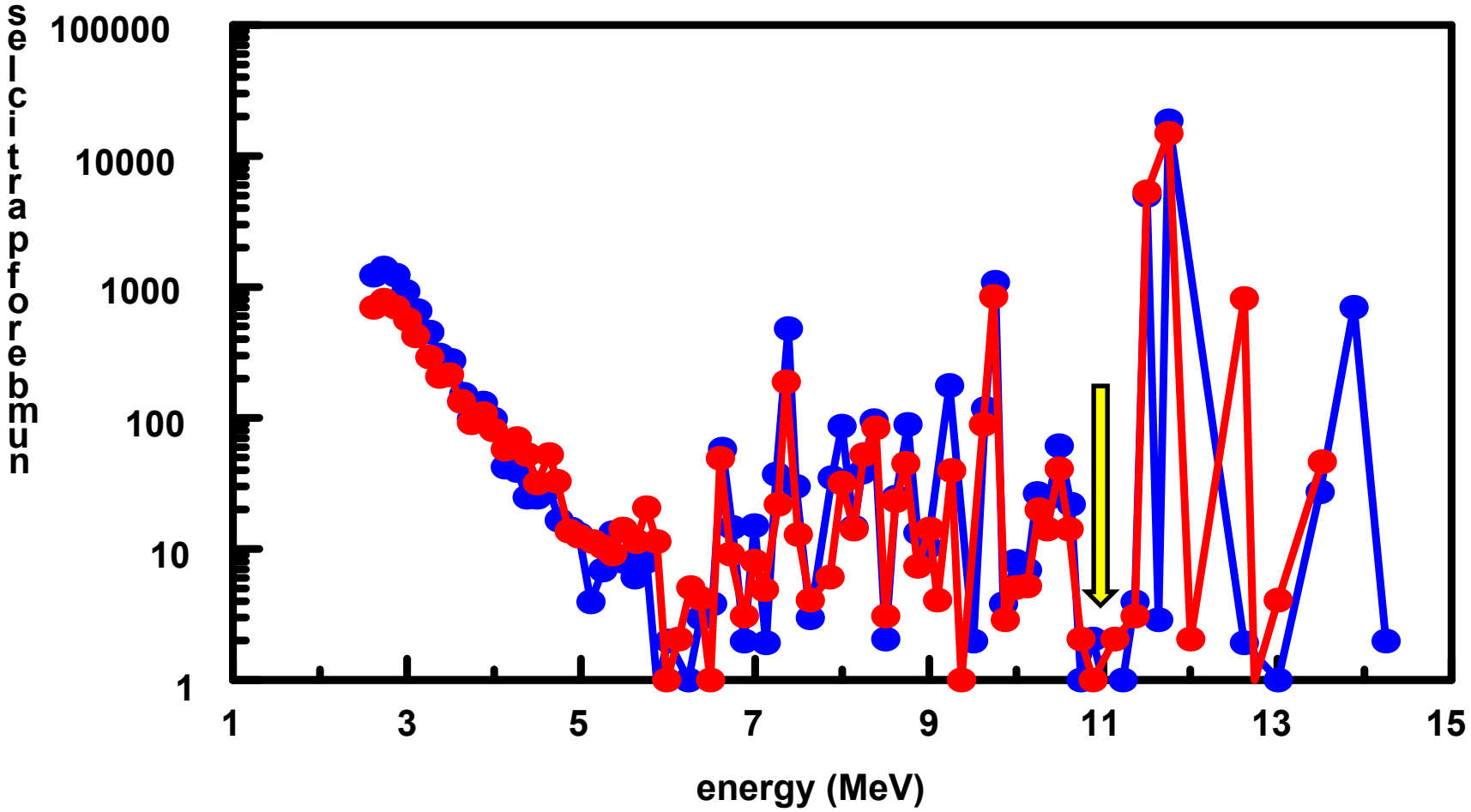
CR-39 outside cell, 14 hr etch

LET Spectrum Analysis (Zhou, NASA)



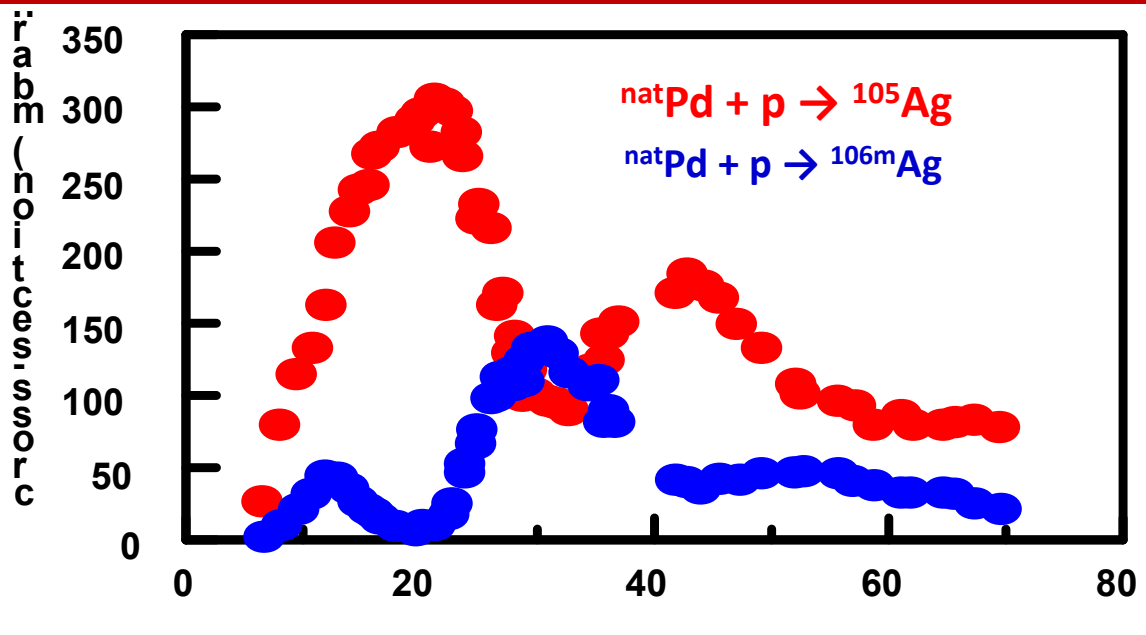


Cause of the Trough at ~ 11MeV?



- The 3.4-14 MeV protons are 12.6-17.5 MeV p that have been slowed down by the Pd, water film, and PE film
- Expect a continuum of energies. But there is a trough at ~11 MeV.
  - This trough suggests that protons with these energies are being consumed

F. Ditrói et al., J. Radioanal. Nucl. Chem., vol 272, 231 (2007)



^{102}Pd – 1.02%
^{104}Pd – 11.14%
^{105}Pd – 22.33%
^{106}Pd – 27.33%
^{108}Pd – 26.46%
^{110}Pd – 11.72%

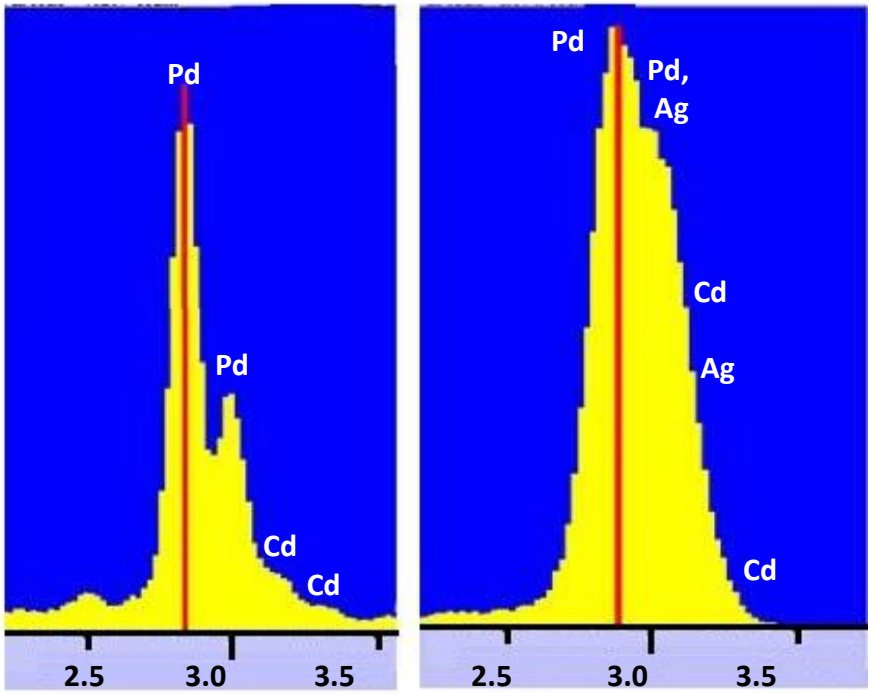
Nuclide	Pd, p Reaction	Half-Life	Decay Mode	Daughter Isotope
^{105}Ag	^{105}Pd(p,n)^{105}Ag ^{106}Pd(p,2n)^{105}Ag ^{108}Pd(p,4n)^{105}Ag ^{110}Pd(p,6n)^{105}Ag	41.29 d	β^+	^{105}Pd
^{105m}Ag	Same as for ^{105}Ag	7.23 min	IT (99.66%) β^+ (0.34%)	^{105}Ag ^{105}Pd
^{106m}Ag	^{106}Pd(p,n)^{106m}Ag ^{108}Pd(p,3n)^{106m}Ag ^{110}Pd(p,5n)^{106m}Ag	8.28 d	β^+ IT (4.16×10^{-6} %)	^{106}Pd ^{106}Ag
^{110m}Ag	^{110}Pd(p,n)^{110m}Ag	249.8 d	β^- (98.64 %) IT (1.36 %)	^{110}Cd ^{110}Ag

Will see Ag that decays back to Pd

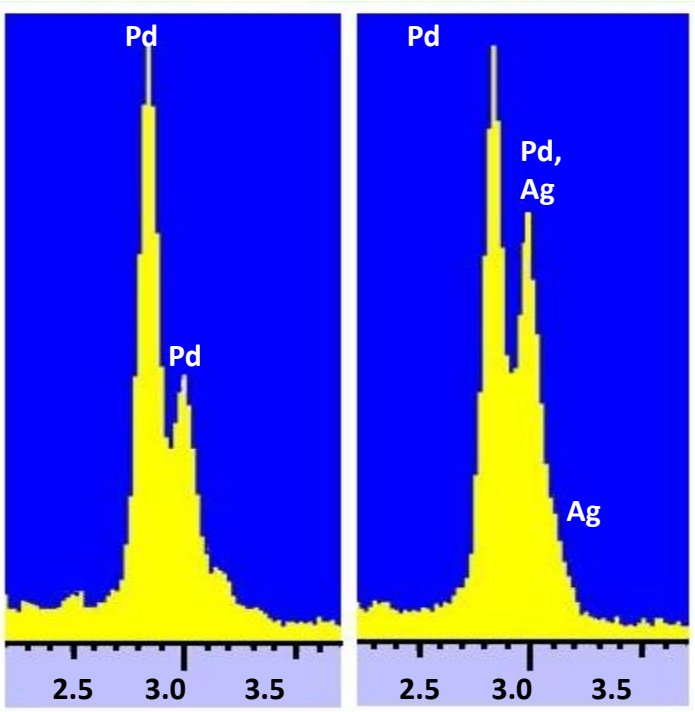
Will see Ag that decays to Cd

J. Dash et al., J. New Energy, vol. 1, 23 (1996); ICCF10; ICCF11

bulk Pd before & after electrolysis



Pd/D co-dep after electrolysis



▼Silver was observed in high, localized concentrations shortly after electrolysis

▼Examination 15 months later showed the presence of cadmium in addition to silver

▼ Changes in ratio between Ag $L_{\beta 1}$ and Ag $L_{\alpha 1}$ peak indicated that Ag is slowly changing to Cd

- The Ag $L_{\beta 1}$ peak overlaps with the Cd L_{α} peaks

Review of Analysis of SRI Detectors

- **Microscopic analysis and Automated Analysis (major/minor axis analysis)**
  - **Neutrons: 2.5 MeV and > 12 MeV**
  - **Charged particles: > 10 MeV protons, energetic alphas**
- **Sequential Etching**
  - **Neutrons: 2.5 MeV**
  - **Charged particles: 3 MeV p^+ , 12 MeV and 16 MeV alphas**
- **Linear Energy Transfer Function Analysis**
  - **Protons: 2.5 – 15 MeV**
  - **Alphas: Continuum of alpha energies, possible neutron recoils**

Three methods of analysis yielded complementary results

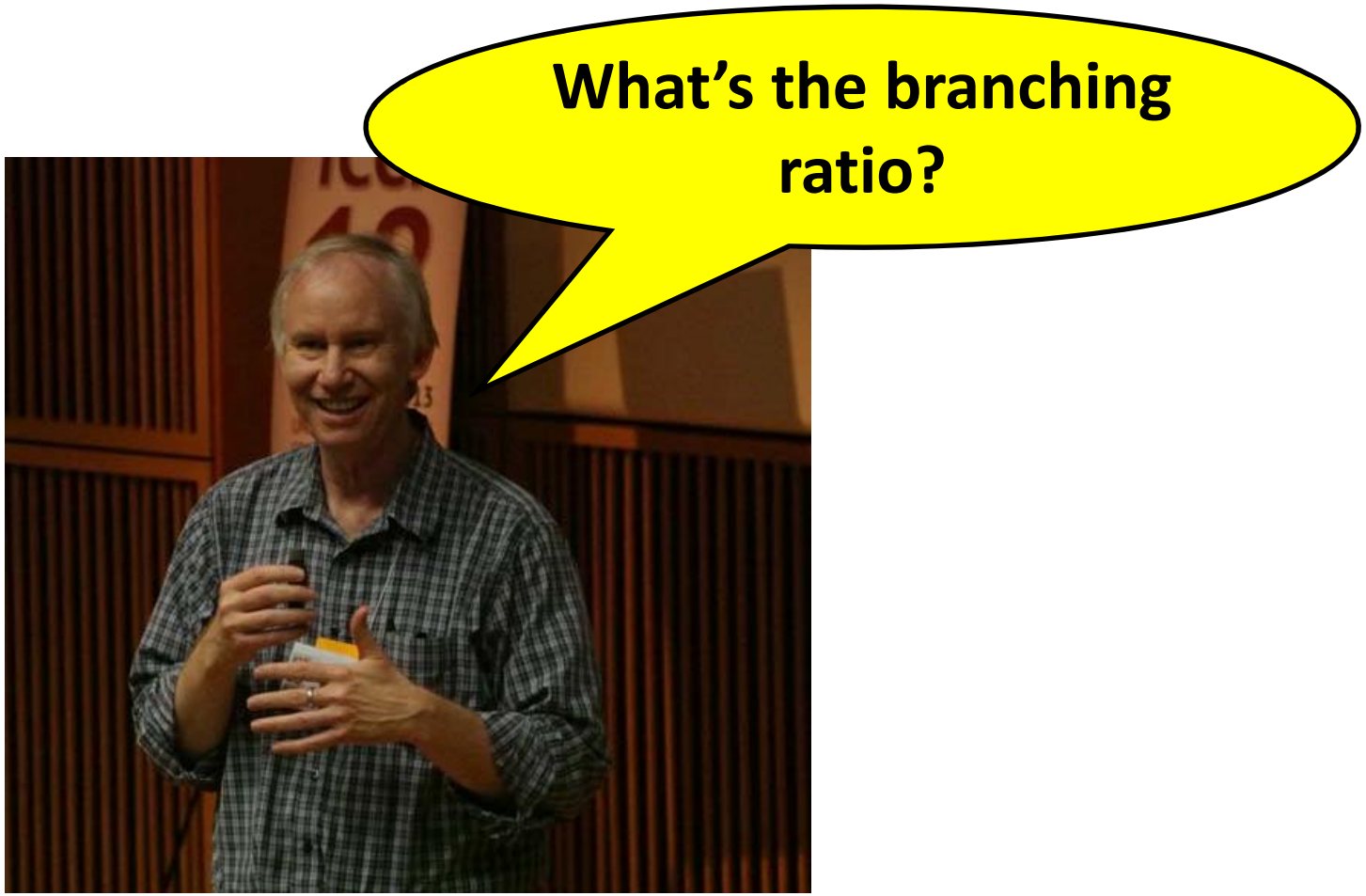
The observed protons and neutrons can be accounted for by the following primary (1 and 2) and secondary (3 and 4) fusion reactions:

$$D + D \rightarrow T\ (1.01\ MeV) + p\ (3.02\ MeV) \quad (1)$$

$$D + D \rightarrow n\ (2.45\ MeV) + {}^{3}He\ (0.82\ MeV) \quad (2)$$

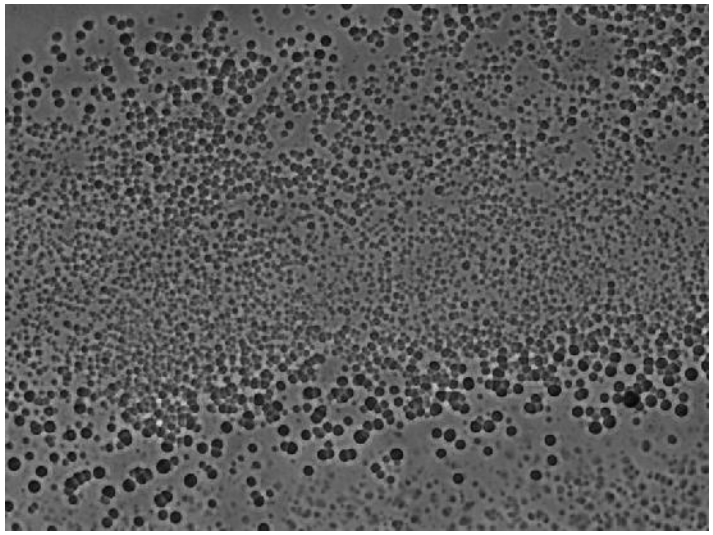
$$D + T\ (\leq 1.01\ MeV) \rightarrow \alpha\ (6.7\text{-}1.4\ MeV) + n\ (11.9\text{-}17.2\ MeV) \quad (3)$$

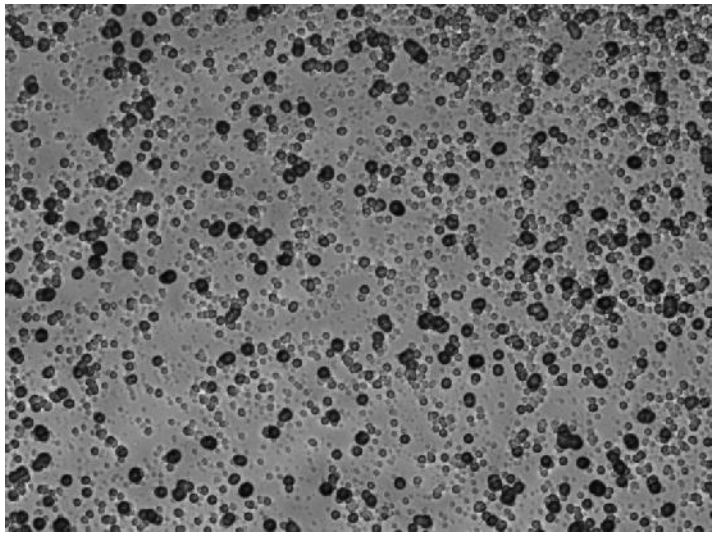
$$D + {}^{3}He\ (\leq 0.82\ MeV) \rightarrow \alpha\ (6.6\text{-}1.7\ MeV) + p\ (12.6\text{-}17.5\ MeV) \quad (4)$$



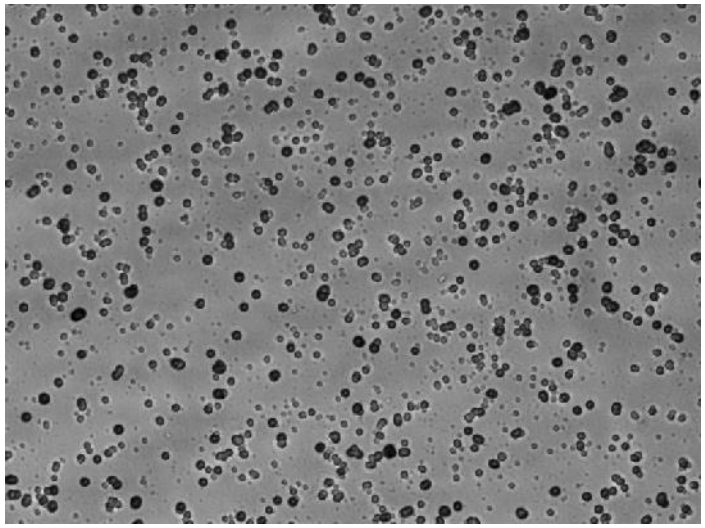
Effect of 60 µm PE Film

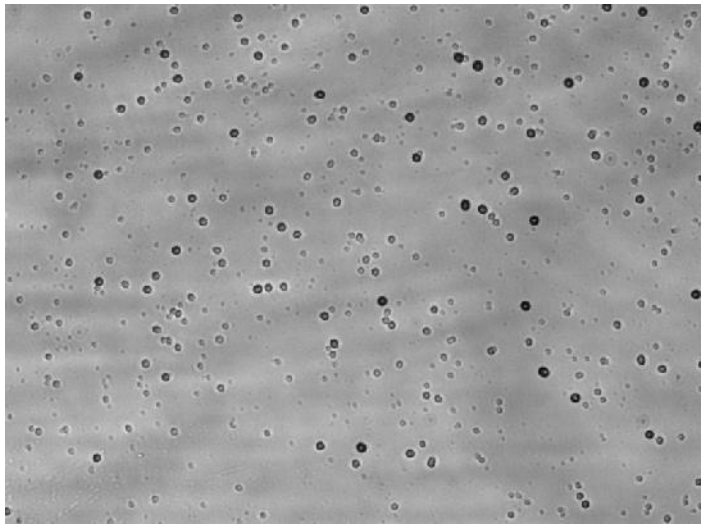
No PE Film



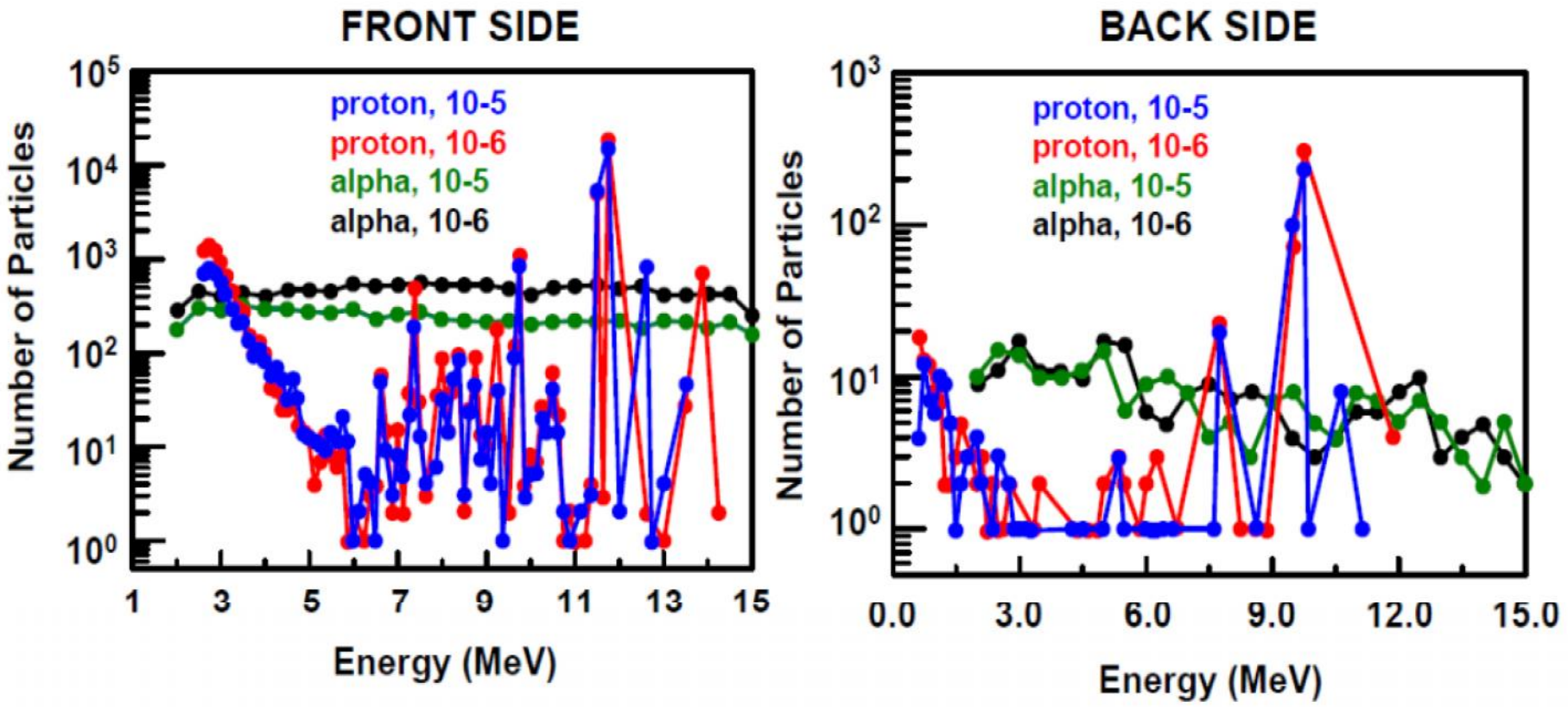


PE film





PE film blocks < 7 MeV α, 0.82 MeV ^{3}He, and 1.01 MeV T



▼Zhou indicated that the effect 60 µm PE film will have on the energies of the charged particles was taken into account

▼LET curves indicate that :

- **> 11 MeV protons will traverse through the 1 mm thick CR-39 detector and PE film**
- **60 µm PE will block 7 MeV alphas**

From Zhou's Analysis (of Both Detectors) :

- The alpha and 0-9 MeV protons tracks (643) on the backside are actually due to neutrons (D + D → ^{3}He + n)
- Frontside alpha tracks (18200) are due to long range alphas (LRA)
  - The 1-7 MeV alphas are due to 7-15 MeV alphas that have been slowed down by the Pd, water film, and PE film
- Frontside p tracks (9873) between 2.6-3.4 MeV due to p (D + D → p + t)
- Frontside p tracks (51734) between 3.4-15 MeV due to p (D + ^{3}He → α + p (12.6-17.5 MeV))
  - The 3.4-12 MeV protons are 12.6-17.5 MeV p that have been slowed down by the Pd, water film, and PE film

Primary Reaction Branching Ratio: Estimated Number of DD Neutrons (10-5 &10-6)

D + D →	T (1.01 MeV) + blocked	p (3.02 MeV) 9873 tracks
D + D →	^{3}He (0.82 MeV) + blocked	n (2.45 MeV) 643 tracks (back) Corrected # tracks = 1286 (front & back) $\varepsilon^* = 1.17 \times 10^{-4}$ $n = 1.1 \times 10^7$

*Neutron efficiency from M.T. Collopy et al., Rev. Sci. Instrum., vol. 63, p. 4892 (1992)

‡ Confirmation: analysis of CR-39 used in Mylar experiment

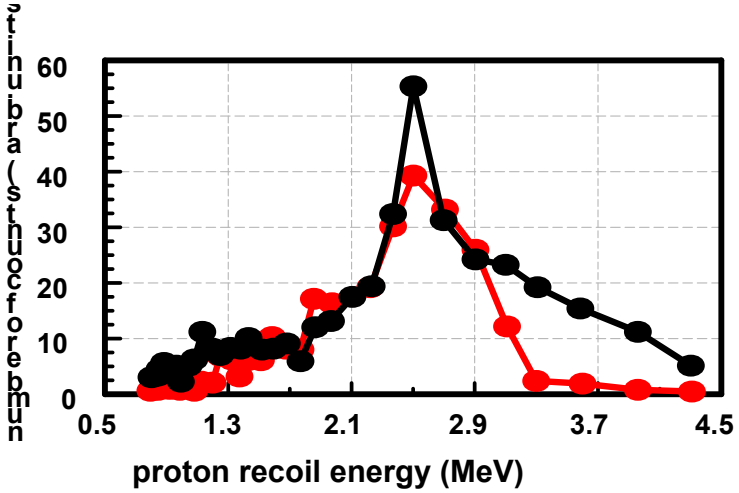
248 DD n tracks

$\varepsilon = 1.17 \times 10^{-4}$

30% of tracks are elliptical

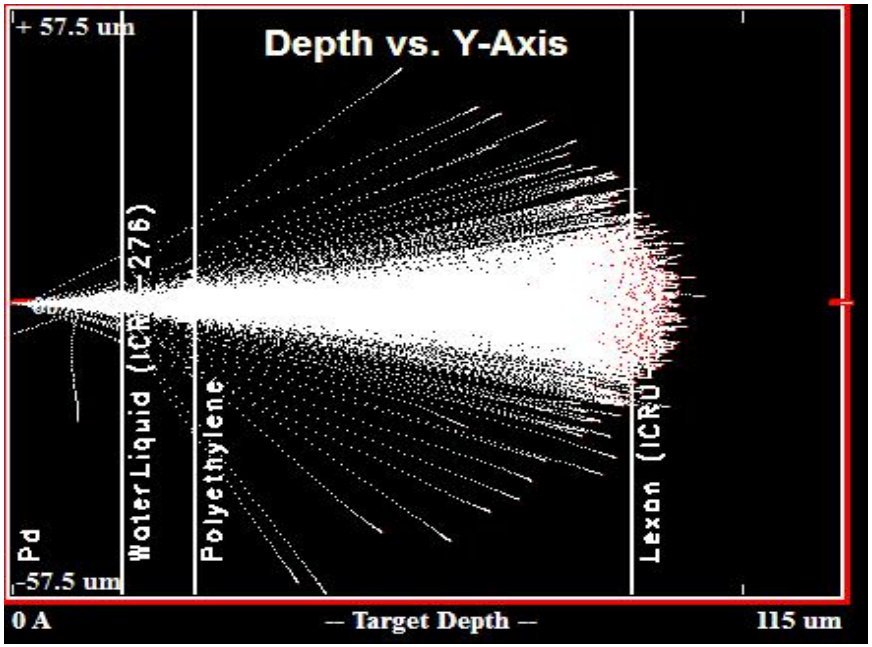
$n = 3.03 \times 10^6$ (for one detector)

$n = 6.06 \times 10^6$ (for two detectors)



Primary Reaction Branching Ratio:
Estimated Number of DD Protons (10-5 &10-6)

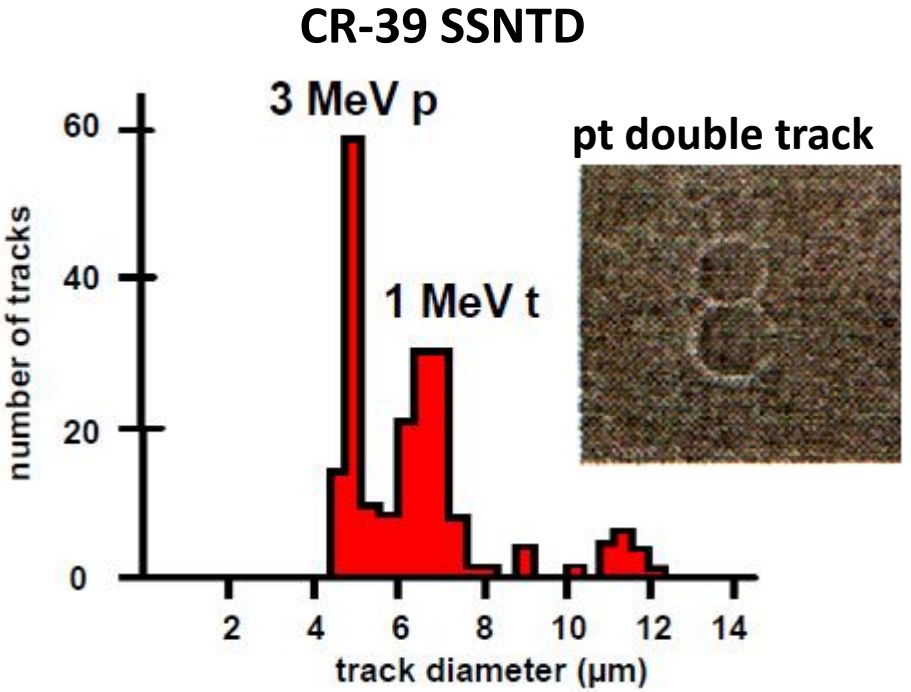
D + D →	T (1.01 MeV) + blocked	p (3.02 MeV) 9873 tracks; Corrected # tracks = 19746 $p > 1.32 \times 10^{6}$
D + D →	^{3}He (0.82 MeV) + blocked	n (2.45 MeV) ‡ 643 tracks (back); Corrected # tracks = 1286 (front & back) $\varepsilon = 1.17 \times 10^{-4}$ $n = 1.1 \times 10^{7}$

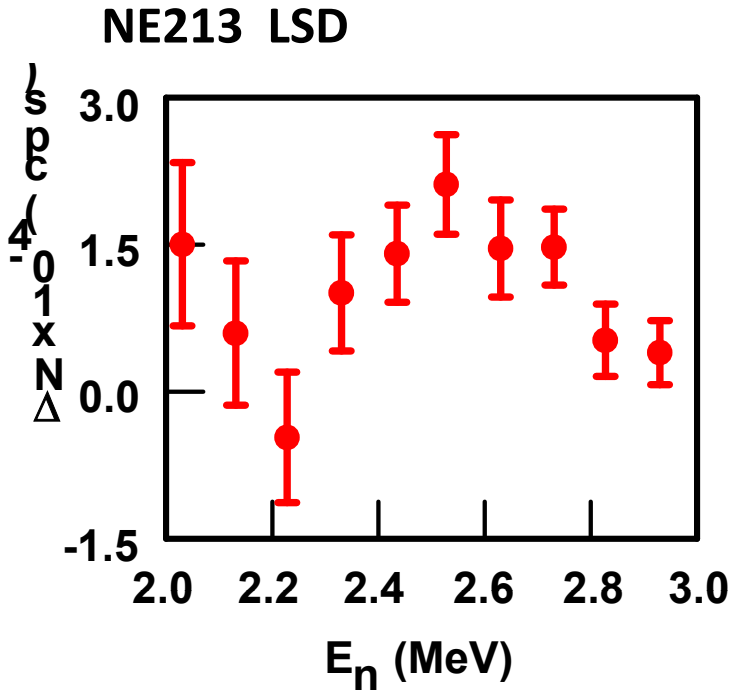


- Approximately half of the tracks were counted by the scanner
- Need to take into account the absorption of charged particles during their escape from the bulk of a thick sample, whose thickness is several times greater than the stopping range of 3 MeV protons in Pd – use TRIM (Transport of Ions in Matter)
- Most of the protons traveling through 15 µm of Pd will reach the detector.
- The Ag/Pd layer is ~ 1 mm thick
- Number of protons is off by a factor of ~66.67

Estimated n/p branching ratio is 8.3. This is the maximum value of the n/p branching ratio as the number p of protons is underestimated

Lipson et al., Fusion Technology, Vol. 38, p. 238 (2000)





▼ Used 40-60 μm thick Au/Pd/PdO heterostructures that were electrochemically loaded

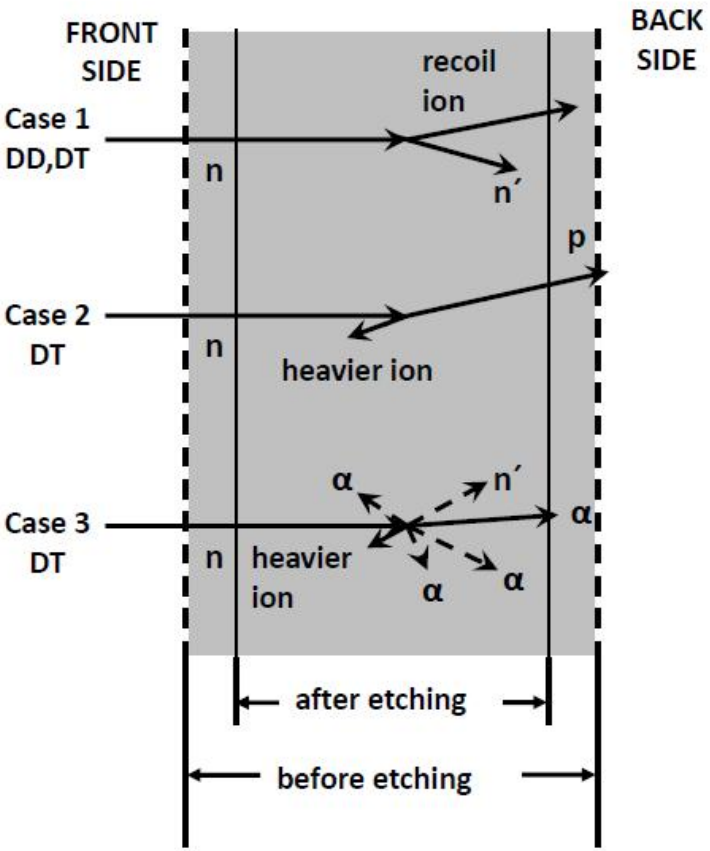
▼ $I_n = (19 \pm 2) \bullet 10^{-3}$ n/s and $I_p = (4.0 \pm 1.0) \bullet 10^{-3}$ p/s in a 4π solid angle

- The lower level of proton emissions is attributed to the absorption of charged particles during their escape from the bulk of a thick sample, whose thickness is several times greater than the stopping range of 3 MeV protons in Pd

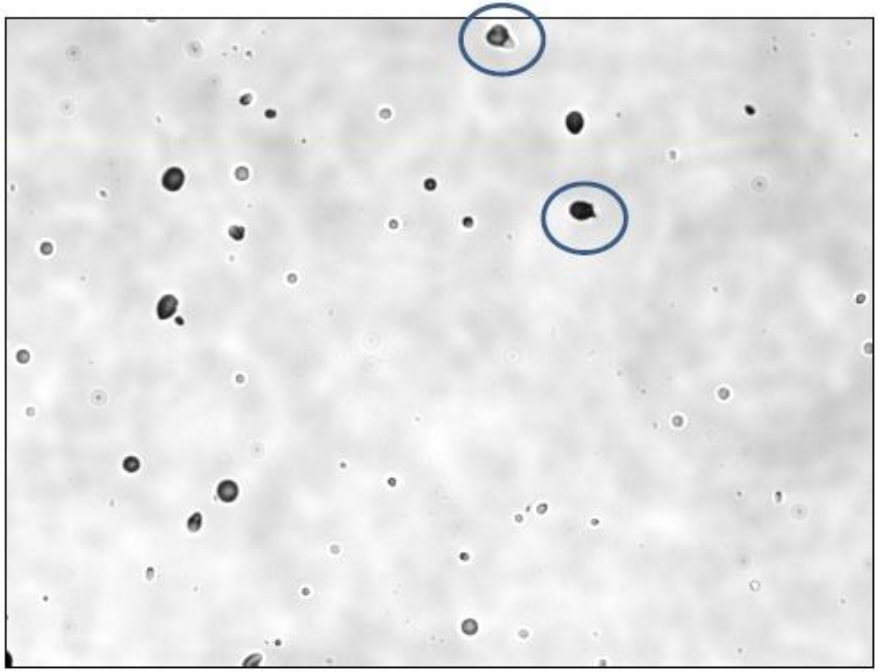
▼ n/p ratio estimated to be 4.75

Secondary Reaction Branching Ratio: Estimated Number of DT Neutrons (10-5 &10-6)

D + T →	α (6.7-1.4 MeV) + blocked	n (11.9-17.2 MeV) 2 triple tracks *$\varepsilon_{DT} = 5.0 \times 10^{-5}$, n = 1.18×10^{6}
D + ^{3}He →	α (6.6-1.7 MeV) + blocked	p (12.6-17.5 MeV) 51734 tracks



*Neutron efficiency from M.T. Collopy et al., Rev. Sci. Instrum., vol. 63, p. 4892 (1992)



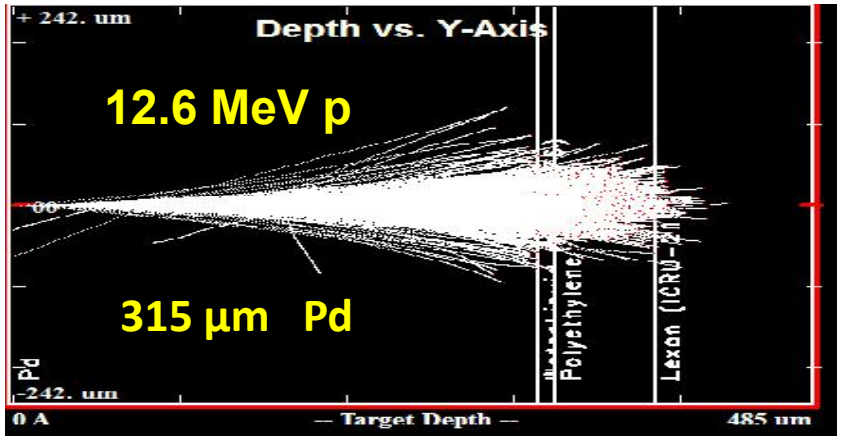
$\varepsilon_{DT} = 5.0 \times 10^{-5}$ is for all three types of interactions

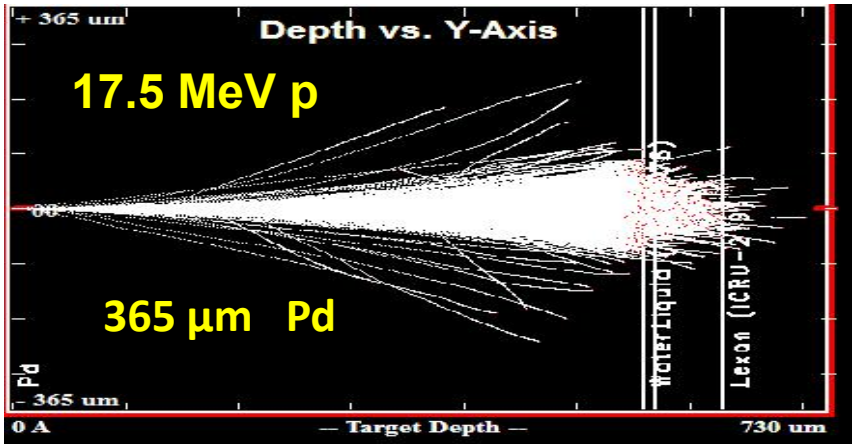
3.38 % of the DT generated tracks were triple tracks

Secondary Reaction Branching Ratio: Estimated Number of D^3He Protons (10-5 &10-6)

D + T →	α (6.7-1.4 MeV) + blocked	n (11.9-17.2 MeV) 2 triple tracks $\varepsilon_{DT} = 5.0 \times 10^{-5}$, n = 1.18×10^{6}

D + ^{3}He →	α (6.6-1.7 MeV) + blocked	p (12.6-17.5 MeV)
		51734 tracks, Corrected # tracks = 103468
		p = 2.83×10^{5} to 3.28×10^{5}





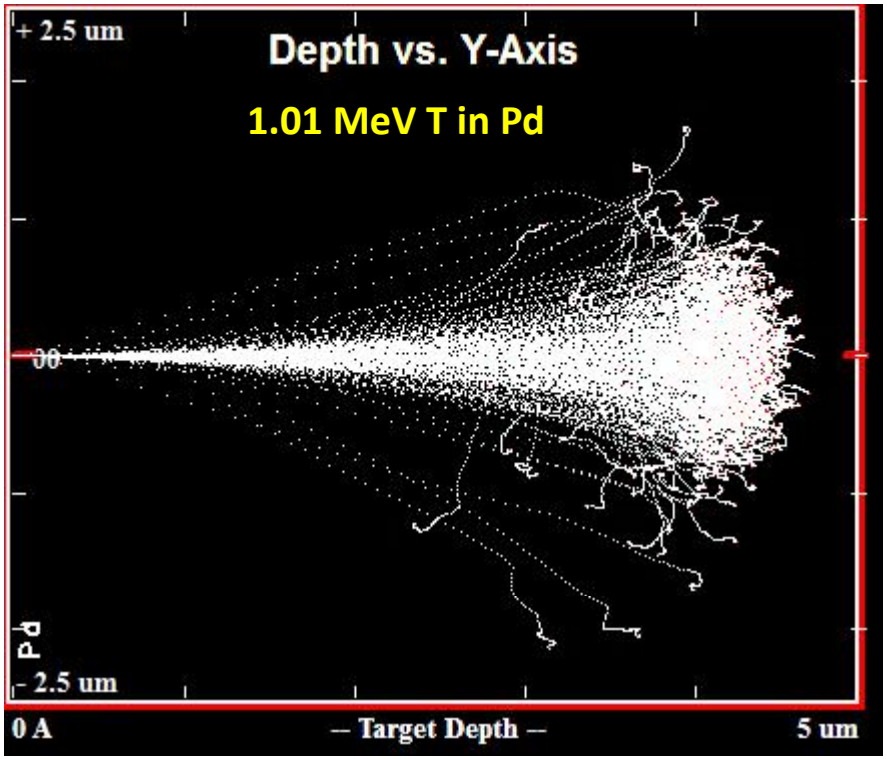
- Approximately half of the tracks were counted by the scanner
- TRIM calculations:
  - —12.6 MeV protons traveling through 315 µm of Pd will reach the detector. The Ag/Pd layer is ~ 1 mm thick. Number of protons is off by a factor of ~3.17
  - —Most of the 17.5 MeV protons traveling through 365 µm of Pd will reach the detector. The Ag/Pd layer is ~ 1 mm thick. Number of protons is off by a factor of ~2.74

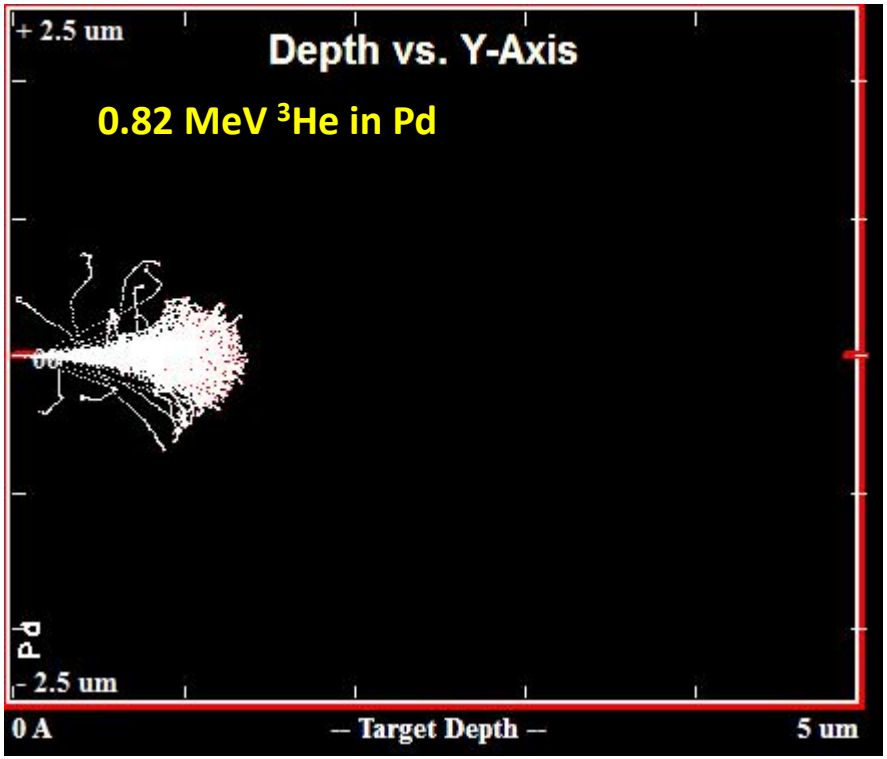
Summary on Branching Ratios

Reagents	Reaction Products	
D + D	T (1.01 MeV) # of tritons > 1.32×10^6	p (3.02 MeV) # of protons > 1.32×10^6
D + D	^{3}He (0.82 MeV) # of ^{3}He = 1.1×10^7	n (2.45 MeV) # of neutrons = 1.1×10^7
D + T	α (6.7-1.4 MeV) # of alphas = 1.18×10^6	n (11.9-17.5 MeV) # of neutrons = 1.18×10^6
D + ^{3}He	α (6.6-1.7 MeV) # of alphas = 2.83×10^5 to 3.28×10^5	p (12.6-17.5 MeV) # of protons = 2.83×10^5 to 3.28×10^5

- Indicates that the primary reactions are approximately equal
- Indicates that DT reactions are slightly favored over ^{3}HeD reactions

Efficiency of Secondary Reactions





Reaction	σ at 10 keV (barn)	σ at 100 keV (barn)	σ_{max} (barn)
D+D → T+p	2.81×10^{-4}	3.3×10^{-2}	0.096
D+D → ^{3}He+n	2.78×10^{-4}	3.7×10^{-2}	0.11
D+T →α+n	2.72×10^{-2}	3.43	5.0
D+ ^{3}He → α+p	2.2×10^{-7}	0.1	0.9

Expect more DT reactions than D^{3}He reactions

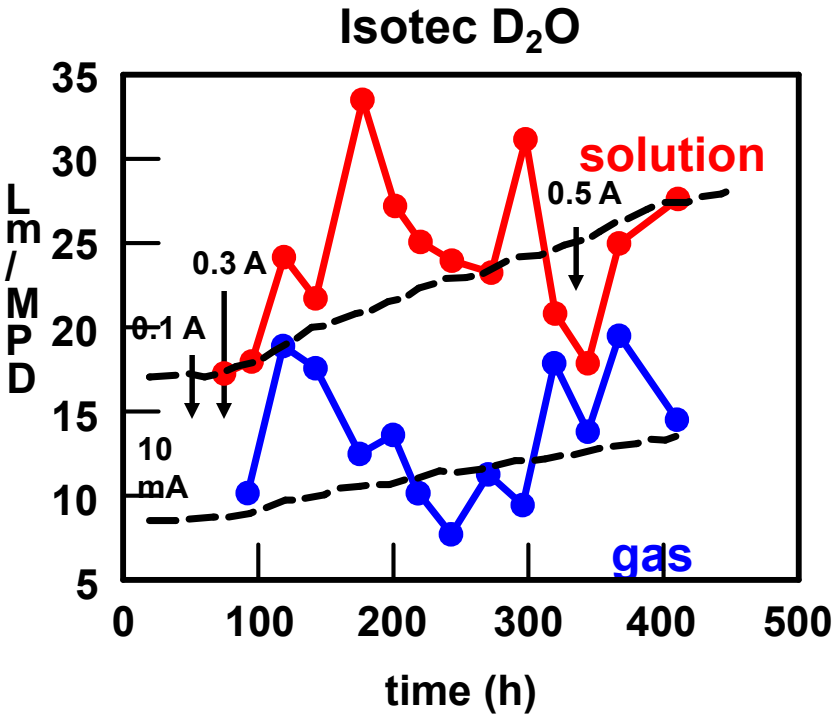
Summary on Branching Ratios

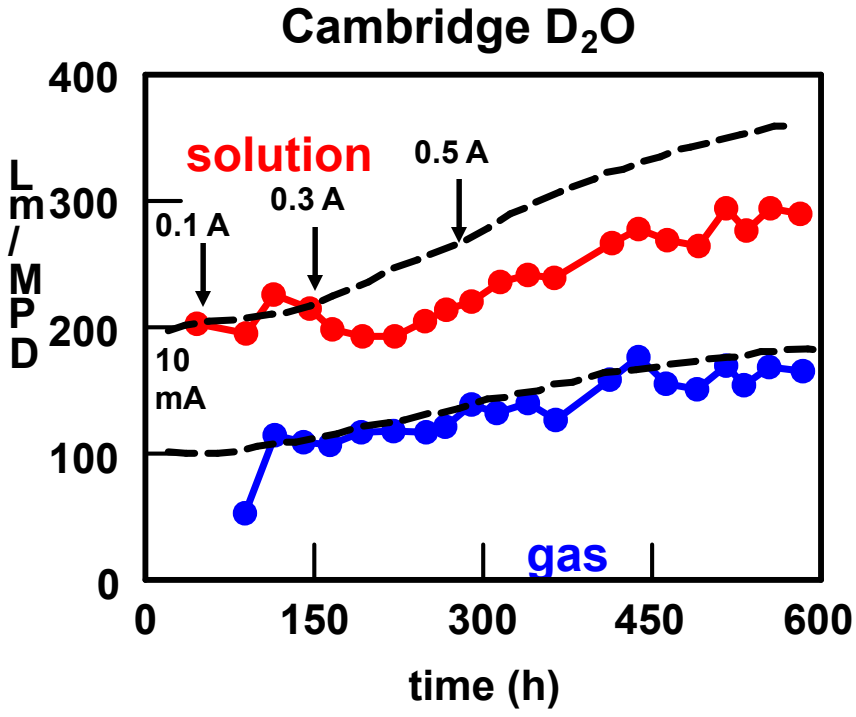
Reagents	Reaction Products	
D + D	T (1.01 MeV) # of tritons > 1.32×10^6	p (3.02 MeV) # of protons > 1.32×10^6
D + D	^{3}He (0.82 MeV) # of ^{3}He = 1.1×10^7	n (2.45 MeV) # of neutrons = 1.1×10^7
D + T	α (6.7-1.4 MeV) # of alphas = 1.18×10^6	n (11.9-17.5 MeV) # of neutrons = 1.18×10^6
D + ^{3}He	α (6.6-1.7 MeV) # of alphas = 1.80×10^5 to 3.18×10^5	p (12.6-17.5 MeV) # of protons = 1.80×10^5 to 3.18×10^5

- Indicates that most of the tritons produced are consumed to create 11.9-17.5 MeV neutrons
  - Secondary reactions have a higher cross section and occur at lower energies compared to primary reactions
  - A 1.01 MeV triton, once born, can go through 4.12 µm Pd – equivalent to passing through 10,236 unit cells in the lattice
  - Bockris has reported seeing a loss of tritium during Pd/D co-deposition

Bockris: Tritium in Pd/D Co-deposition

ICCF3 (1992)





▼ Dashed lines indicate the calculated expected concentrations of tritium in the solution and gas phases.

▼ Pd/D co-dep on Au: 6 out of 9 experiments showed tritium production

▼ Tritium production was observed when low tritiated D_2O was used.

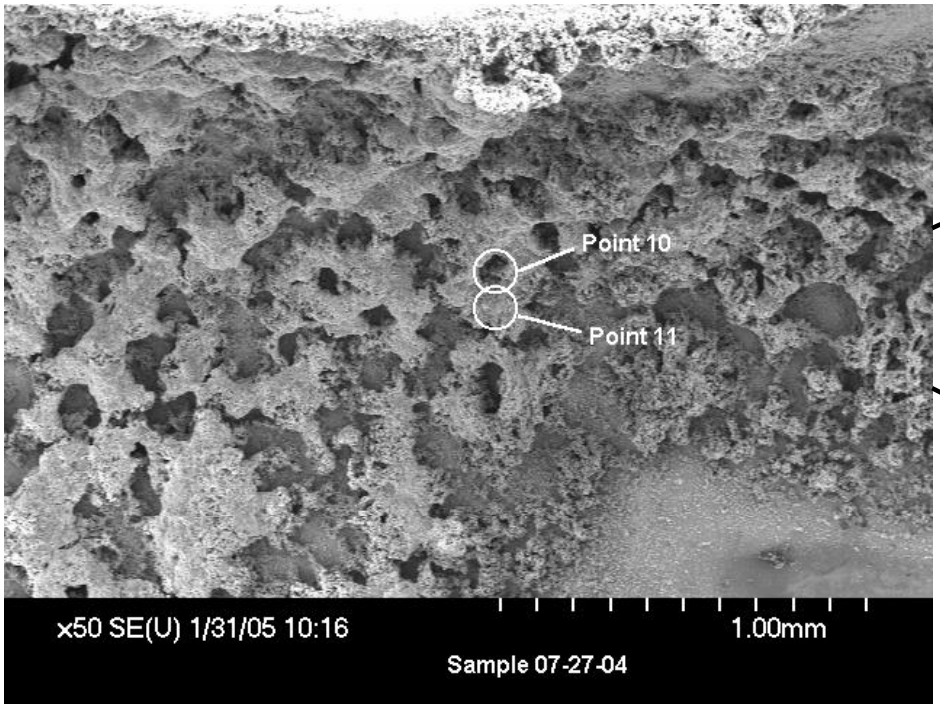
- A burst of tritium was observed in the gas phase. At the same time, or with a slight delay, a bust of tritium occurred in the solution phase.
- A loss of tritium was observed in the solution phase when high tritiated D_2O was used. Suggests that the tritium is being consumed

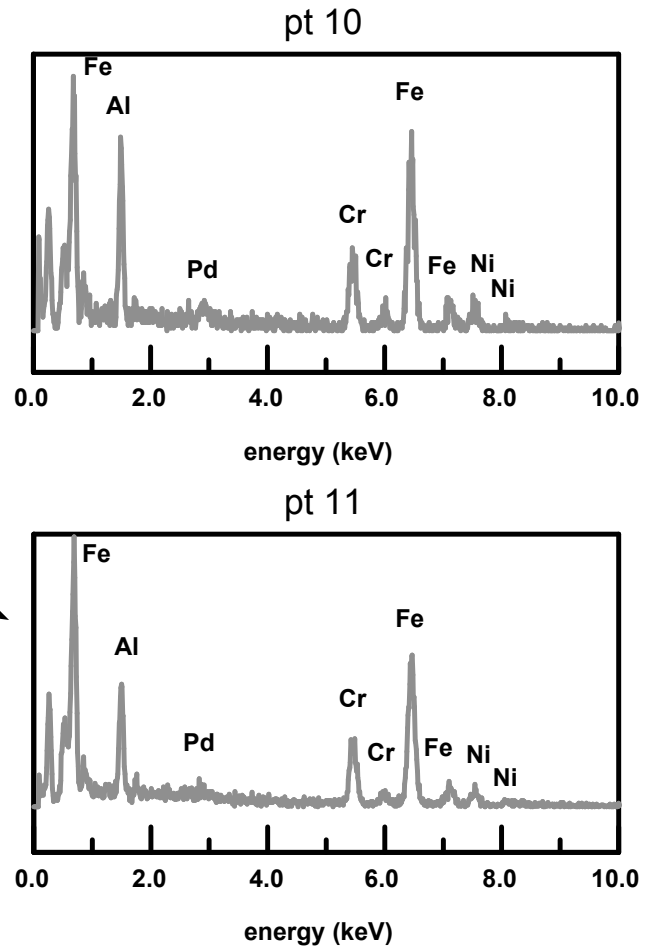
▼ At ICCF17, Koreans reported similar results using closed cells

In all the experiments the newly found elements or isotopes appear to be explainable through occurrence of multiple deuteron captures in one or more of the isotopes of the high Z elements in/on the cathode, followed by fission of some of the complex intermediate compound nuclei.

Transmutation

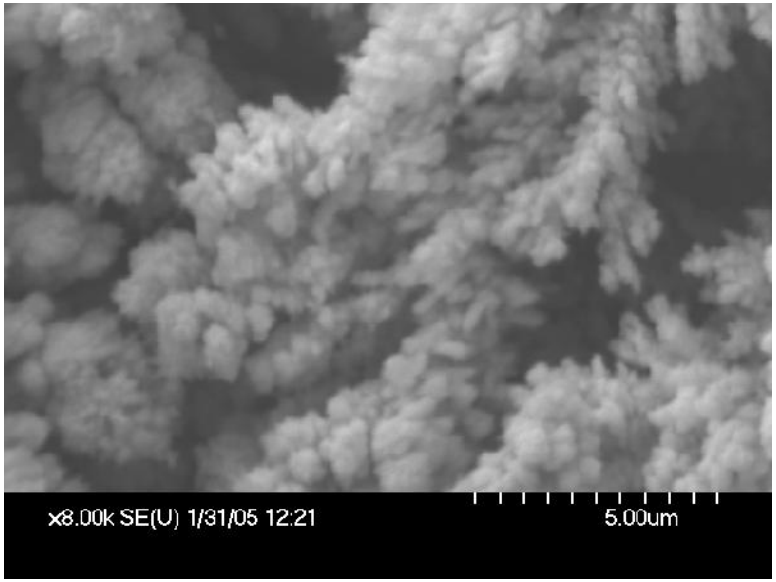
Au/Pd-D, external B field

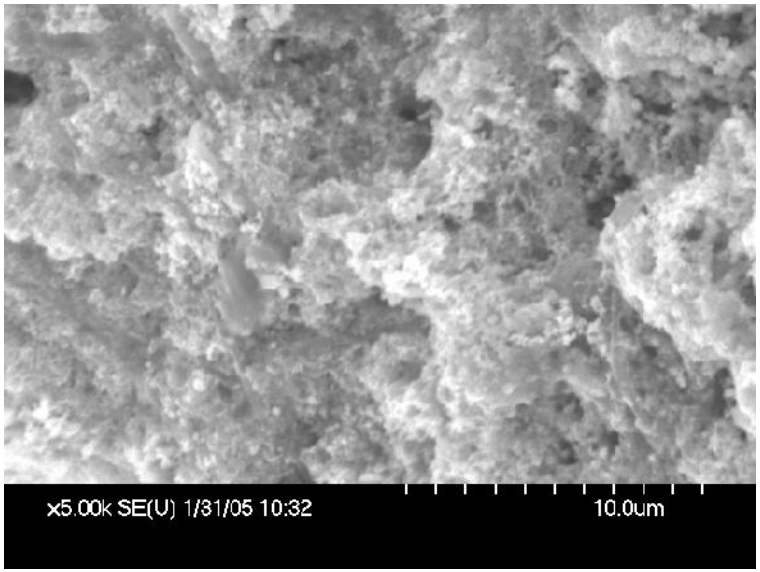


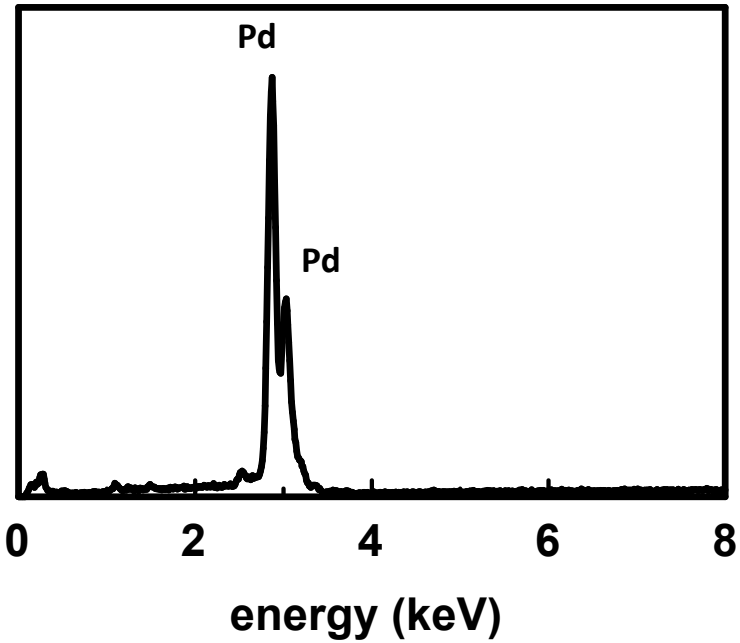


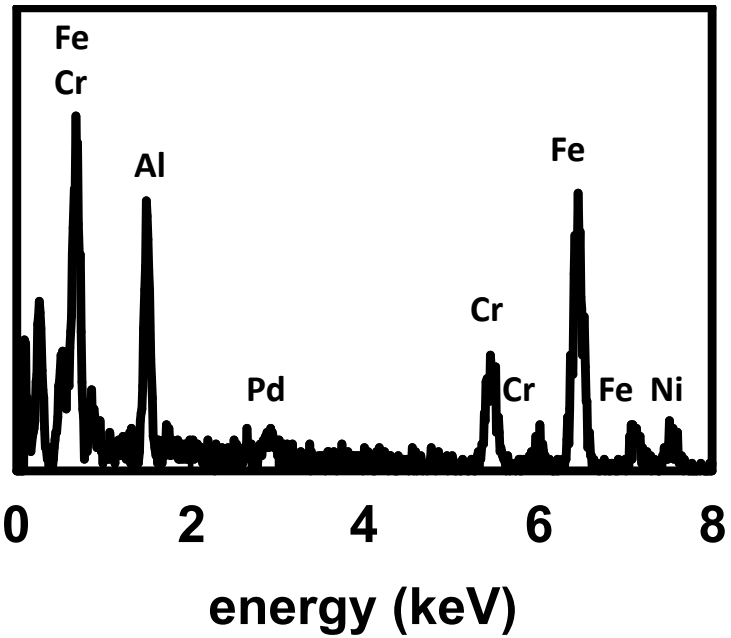
- Lorentz forces cause the deposit to form star-like features
- EDX shows a small Pd peak and the presence of Fe, Cr, Ni, and Al
  - — EDX detection limits are on the order of 0.1%
  - —Distribution on new elements is inhomogeneous
  - — These same elements have been reported by others using a wide variety of conditions
- Are the new elements the result of multi-body deuteron fusion or the disintegration of the Pd lattice?
  - —The relative size of the Pd peak suggests the latter

Different Spots on the Same Cathode

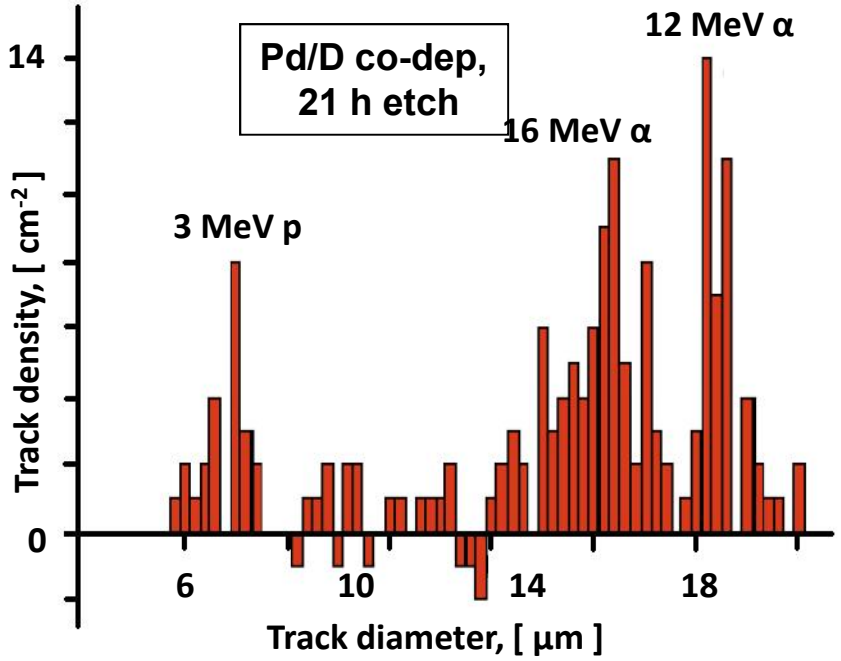


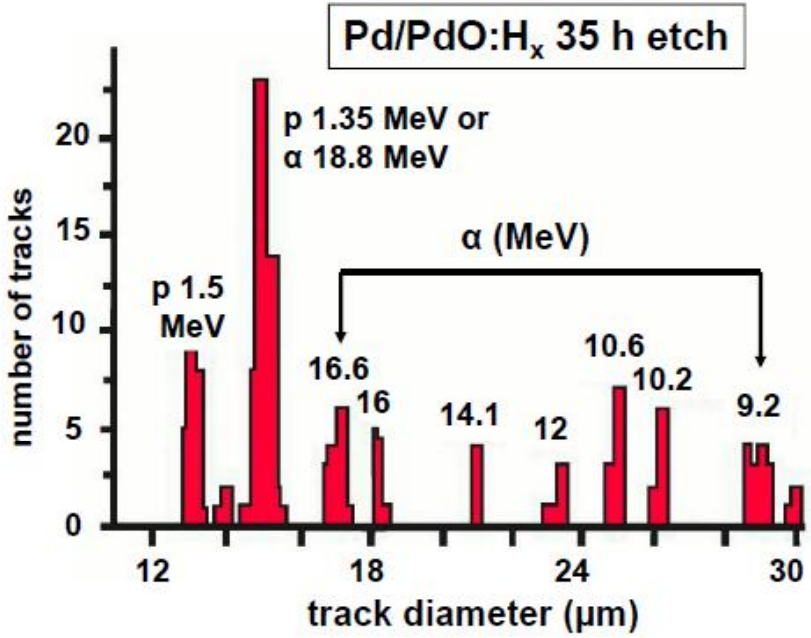






The Smoking Gun





- Fission reactions produce 7-16 MeV alphas (long range alphas)
- As the source of the long range alphas is fission, it is very likely that the new elements observed in the EDX spectrum result from fissioning of Pd

Conclusions

- CR-39 detectors, used in Pd/D co-deposition experiments, were subjected to microscopic analysis, automated scanning, sequential etching, and LET spectrum analysis to identify the particles responsible for the tracks
  - Particles identified were 2.45 MeV neutrons, 3-10 MeV protons, 2-15 MeV alphas, and 14.1 MeV neutrons
- Nature of the nuclear reactions
  - Protons, neutrons, and 2-7 MeV alphas observed in CR-39 detectors used in Pd/D co-deposition have energies consistent with those obtained from primary and secondary fusion reactions
  - Branching ratio of primary reactions is close to unity
  - DT reactions are favored over ^{3}HeD reactions
  - Transmutation is probably the result of fissioning of the Pd nucleus. This is supported by the observation of long range alphas (7-15 MeV)

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