Laboratory Nuclear Astrophysics

Studying fusion reactions at characteristically low energies is needed to understand stellar processes and may be a key to understanding primordial formation, nucleosynthesis of the elements, and may give clues to fusion energy technology.

Rolfs, Trautvetter and Rodne. **Current status of nuclear astrophysics.** Rep. Prog. Phys. **50 (1987)**

"… is often a frustrating science. The desired cross sections are among the smallest measured…"

"… often requiring long data collection times with painstaking attention to background.

"From a purely nuclear point of view, the reactions studied are often of comparatively little interest.

"… has provided unexpected intellectual rewards in nuclear physics itself."

… requires specialized equipment and environments

Nuclear Physics in Astrophysics V IOP Publishing
Journal of Physics: Conference Series **337** (2012) 012062 doi:10.1088/1742-6596/337/1/012062

Electron screening effects in nuclear reactions: still an unsolved problem

J Cruz[1,2], H Luís[1,2], M Fonseca[1,2] and A P Jesus[1,2]

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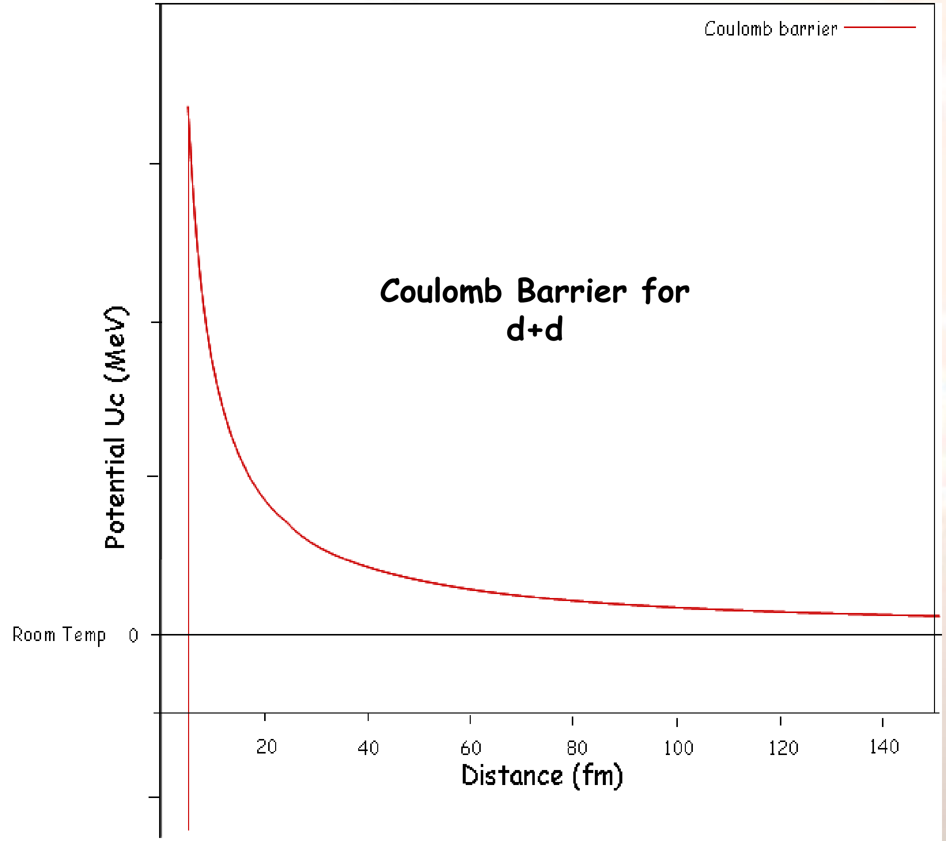
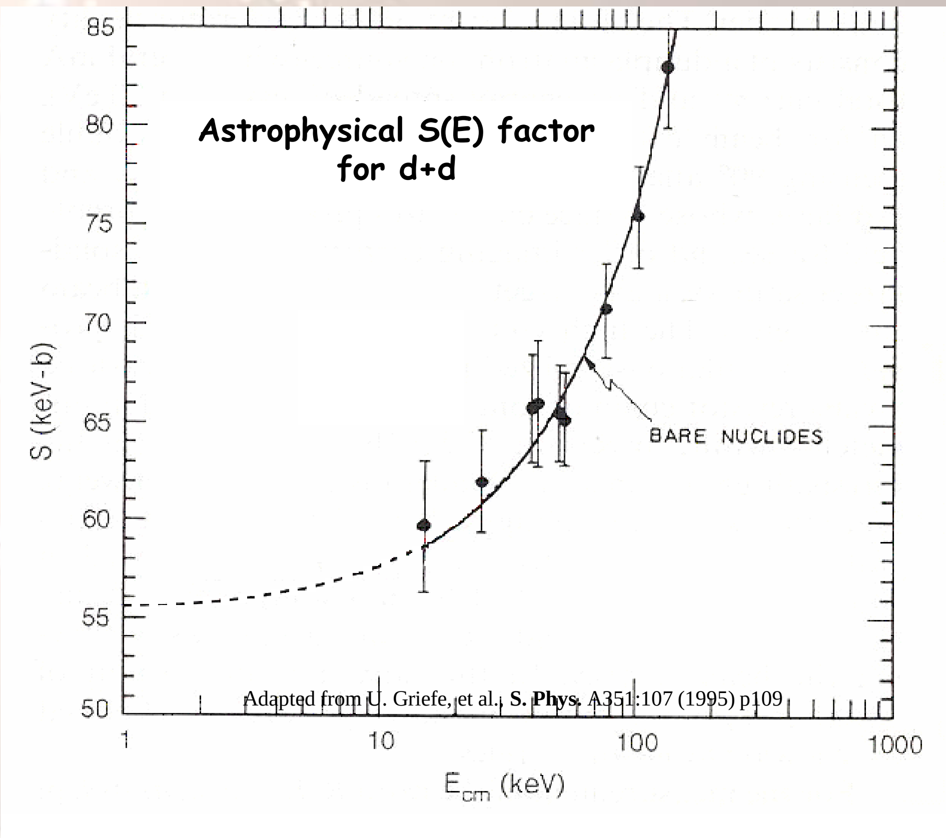
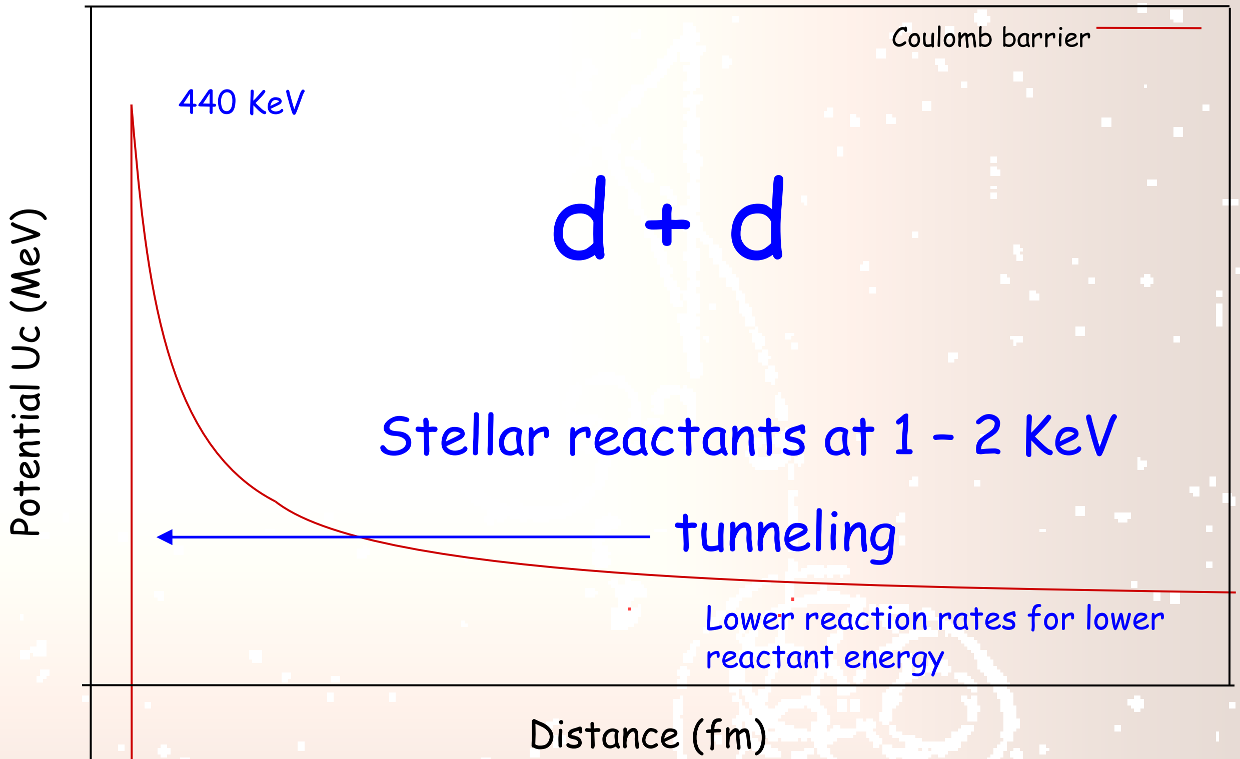
Abstract. Electron screening for nuclear reactions in metals plays an unexpected and important role in enhancing reaction cross sections in the ultra-low energy region. Even though there are still some discrepancies between experimental data from different authors, the enhanced screening effect in metallic environments is well established, and attributed to the quasi-free valence electrons in the metals. However, there is still no solid theory which can describe quantitatively the observed enhancements. In the present work, experimental and theoretical results obtained so far will be overviewed, and a proposal to improve our knowledge on this subject.

Laboratory Nuclear Astrophysics





Unbound Reactants



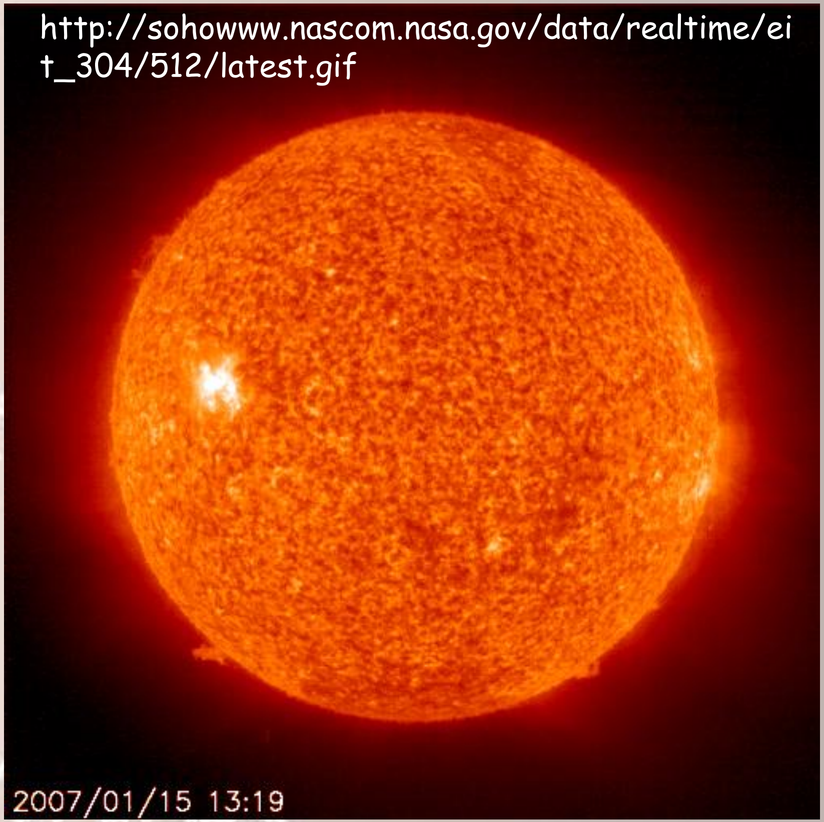
$\rightarrow$ n(2.54 MeV) + ^{3}He (0.82 MeV) 1:2

$\rightarrow$ p(3.02 MeV) + t (1.01 MeV) 1:2

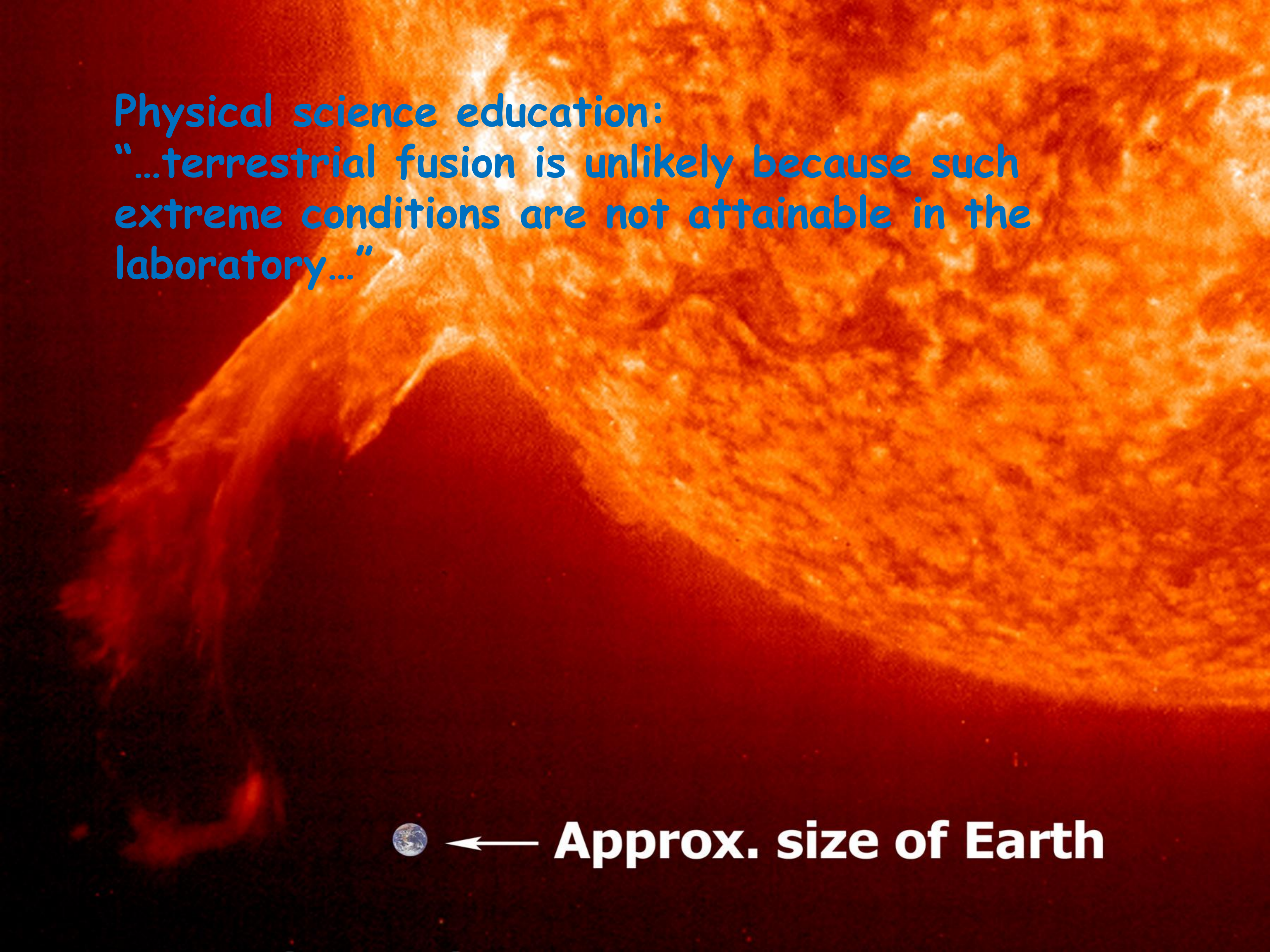
$\rightarrow$ ^{4}He + γ (24 MeV) 1:10^6

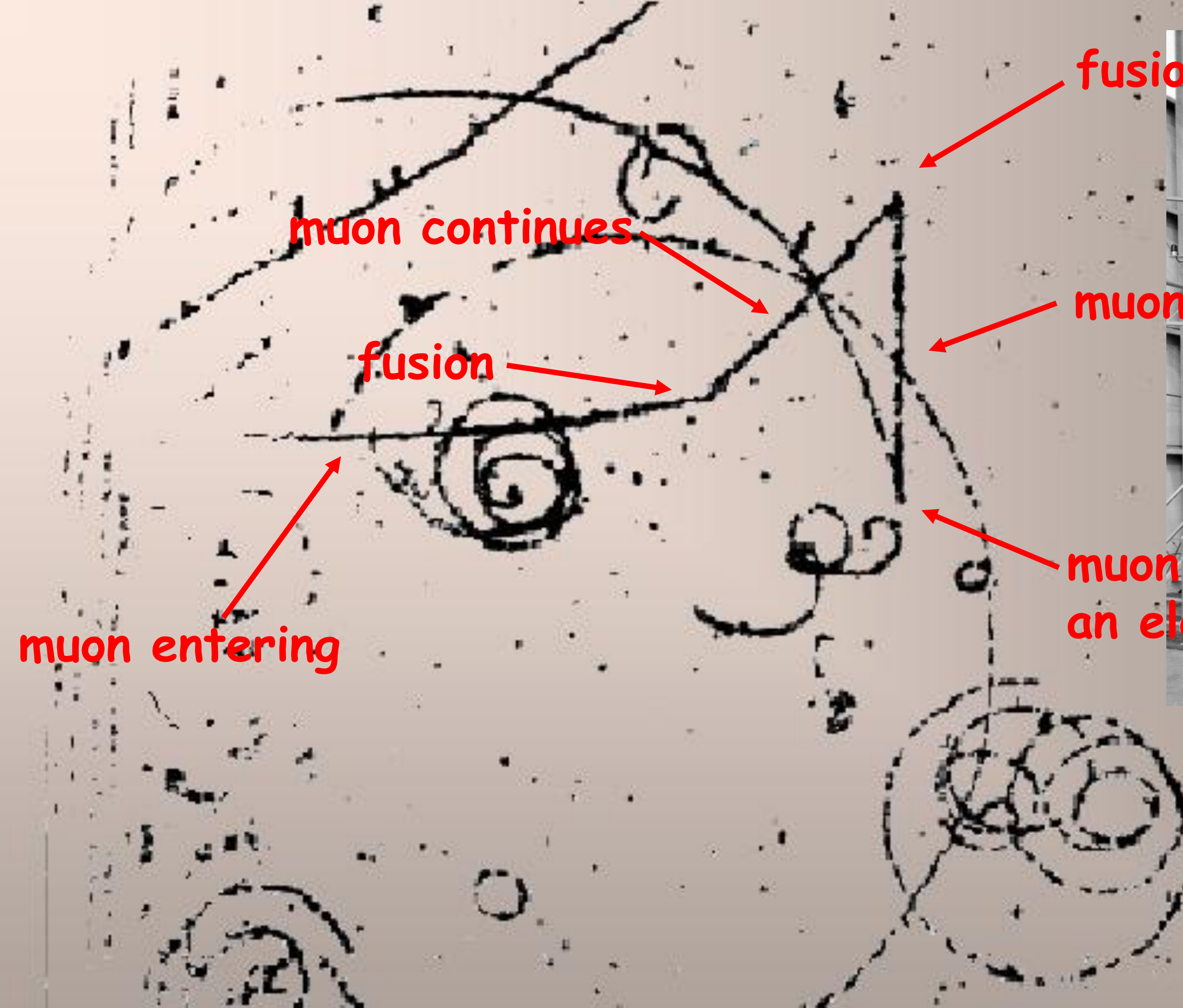
Stellar Fusion

- Mass of the sun is 2 $X10^{30}$ Kg of which 74% is H
- Density of sun's core is 150,000 Kg/M^3 or about 10^{11} atmospheres
- Only one in 10^{18} - 10^{22} hydrogen atoms per second fuse
- Core temperature of 13,000,000 K to 18,000,000 K or about 1KeV to 2KeV



Physical science education:
"…terrestrial fusion is unlikely because such extreme conditions are not attainable in the laboratory…"

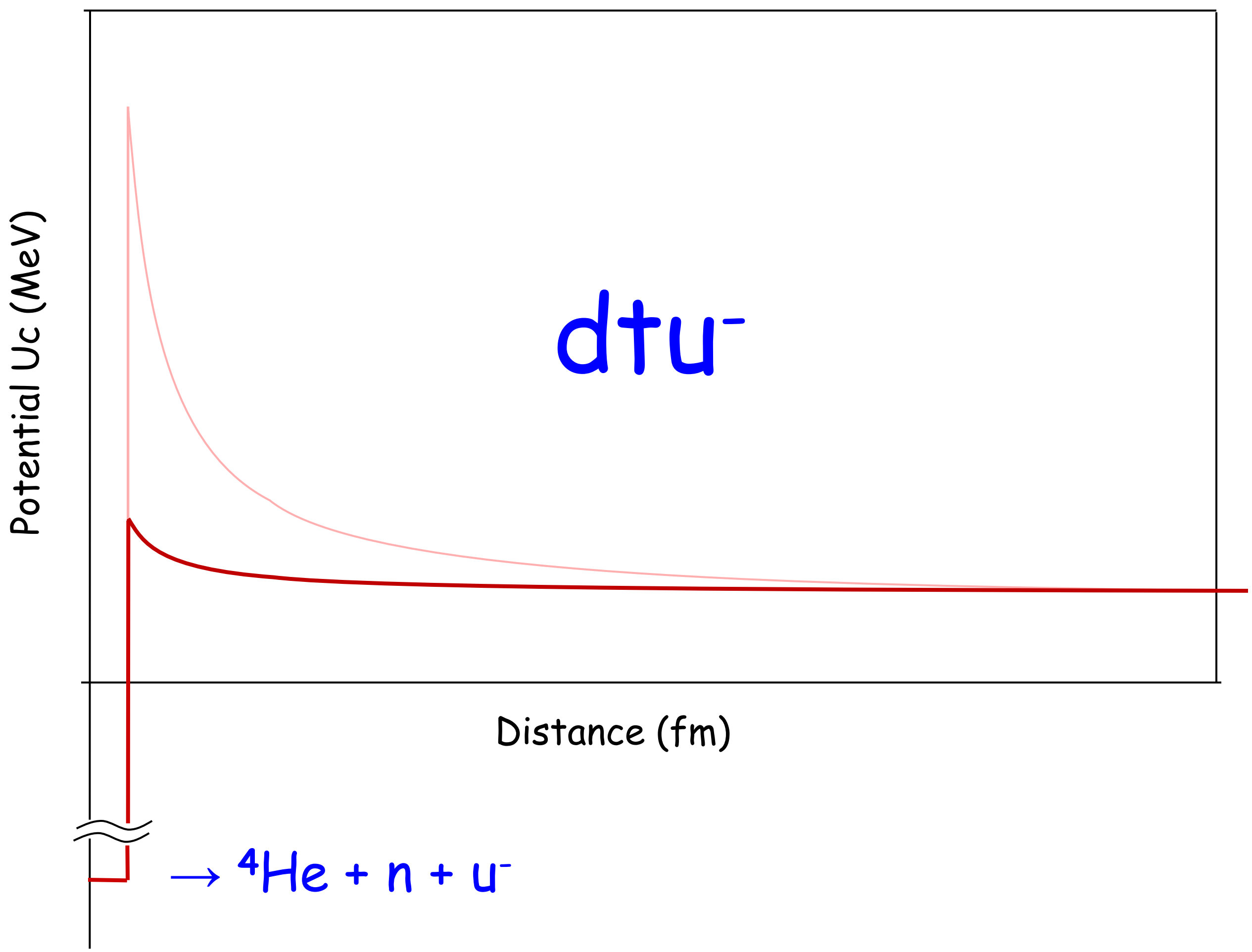




http://dsd.lbl.gov/

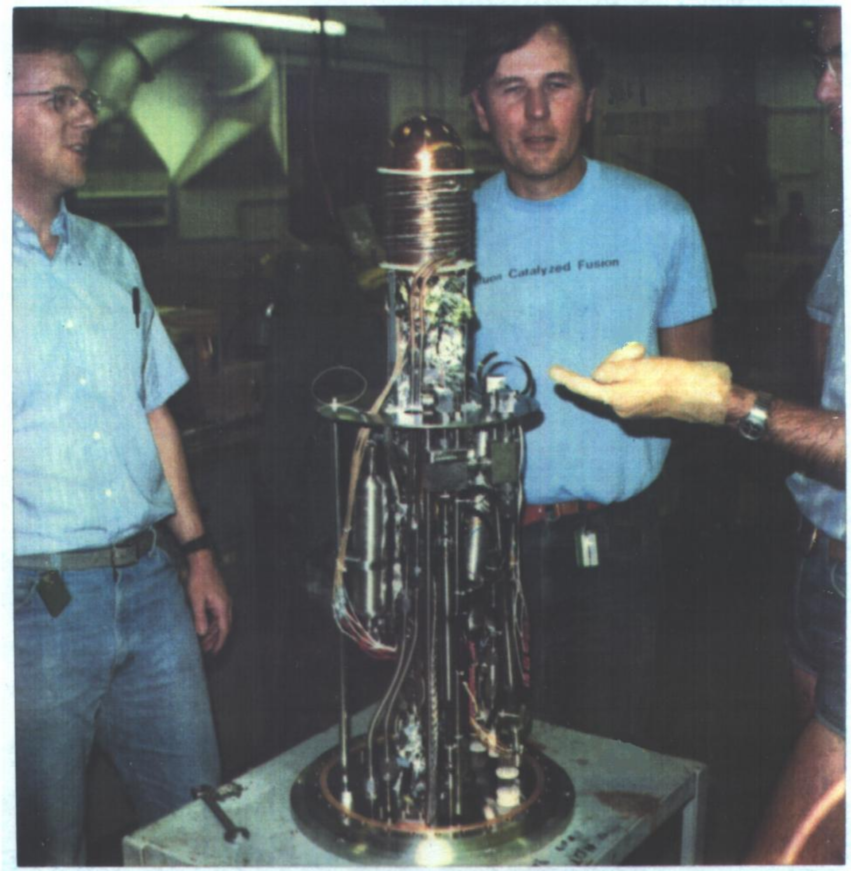
First observed by Luis W. Alvarez et. al. at UC Berkeley in 1956
hydrogen bubble chamber: p + d + u- → 3He + u-

Bound Reactants – Muon Catalyzed Fusion

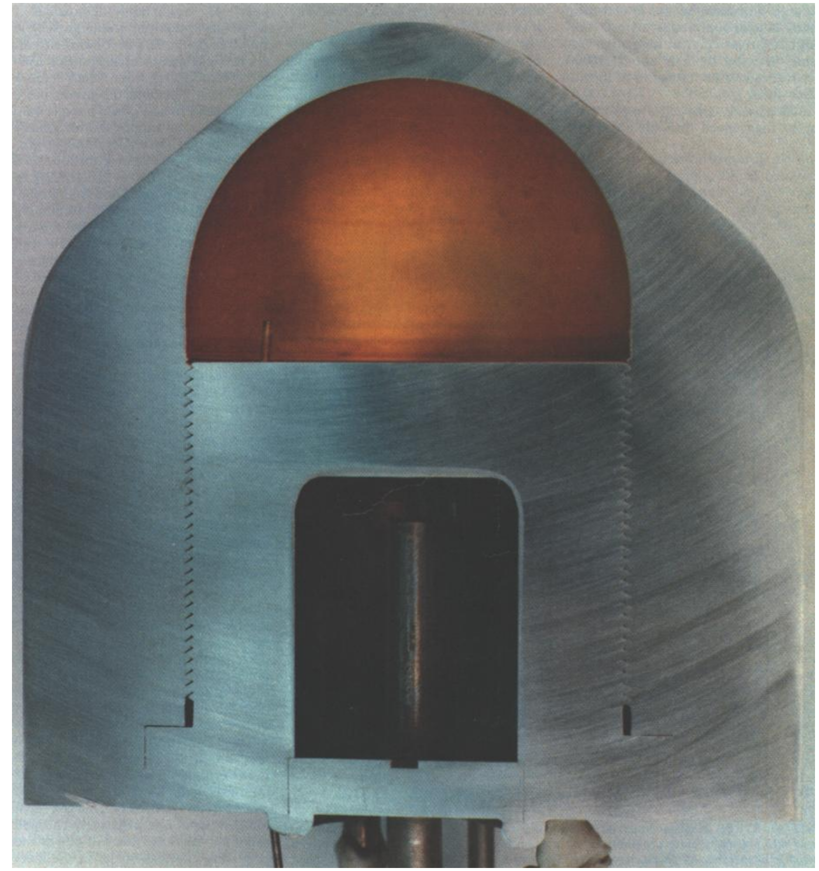


1957 J D Jackson predicted ~100 fusions per muon, later corrected to much less due to the "alpha sticking problem." → experiment needed…

DOE sponsored test for reaction rates by BYU, INEL, and LANL



Steven Jones (PI), Gus Caffrey, & Mike Paciotti
Los Alamos Meson Physics Facility



3000 atm chamber up to 450K
1986 Achieved >150 fusions / muon (average rate)

Inspiration: nuclear fusion is possible in condensed matter!

<u>Cold Nuclear Fusion</u>. Johann Rafelski and Steven E. Jones, *Scientific American*, **257**, 84 (1987).

Steve Jones gives a colloquium talk March 12, 1986

Reports on muon catalsis and speculates on other possible bound fusion processes: "...possibility of fusion in Jovian metallic hydrogen core"

S.E. Jones and J.E. Ellsworth, "Cold (metal-enhanced) fusion, geo-fusion, and cold nucleosynthesis", **Condensed Matter Nuclear Science**, 2005, London: World Scientific, p. 617.

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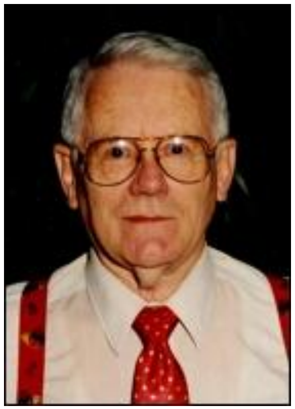


E. Paul Palmer

Mar 13 1986 Source of volcanic heat.

Colloquium yesterday by Steve Jones of BYU physics set me thinking. He talked of muon catalyzed cold fusion — among other things such as quark search and electron-catalyzed fusion of HD molecules. He talked of spontaneous fusion under pressure (low) and catalyzed fusion (high).

$$H + D \rightarrow {}^{3}He + \sim 6\ MeV$$ (I believe.)

Well, when earth's sedimentary material at a continental margin gets pulled down in a subduction zone at a plate boundary, fusion could take place as the pressure increased.

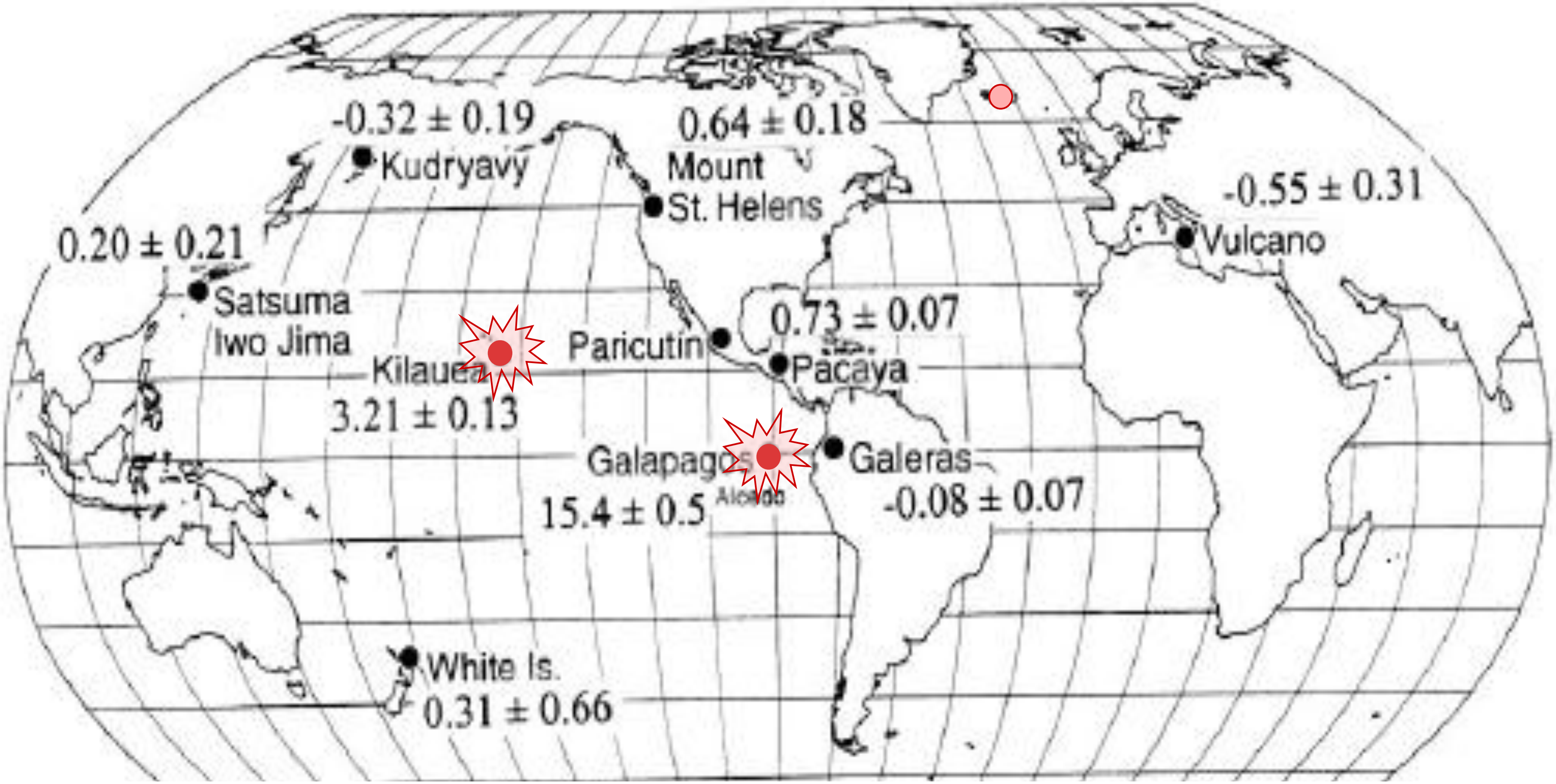
To measure all this, measure the ^{3}He that outgasses from the lava! Simple. These data must be available. The ratio of H to ^{3}He that outgasses would allow computation of the fraction of spontaneous fusions per average water molecule.

Perhaps the rock catalyzes the reaction! Temperature separates H and D from water and even Oxygen might catalyze.

S.E. Jones and J.E. Ellsworth, "Cold (metal-enhanced) fusion, geo-fusion, and cold nucleosynthesis", **Condensed Matter Nuclear Science**, 2005, London: World Scientific, p. 617.

BYU Geo-Fusion hypothesis:

volcanic waters were sampled for tritium content (Tritium



It's been a tritium half-life since tested – time to test again.

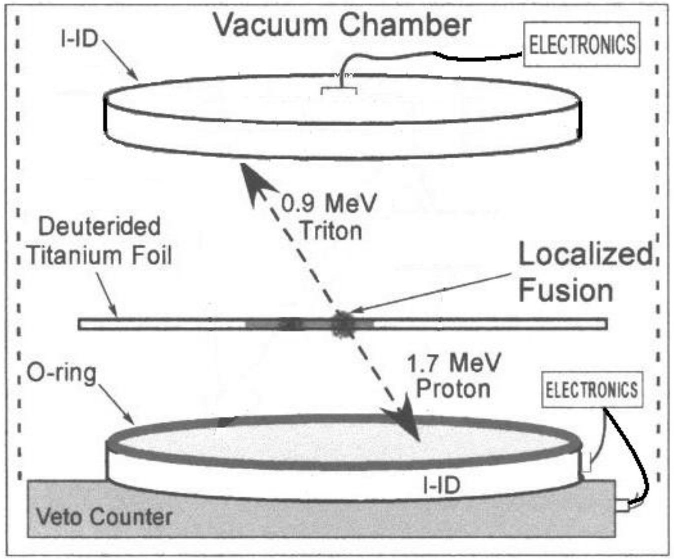
F. Goff, G. M. McMurty / Journal of Volcanology and Geotheraml Research 97 (2000) 347-396

(The tritium unit (TU) is the unit of measure of tritium in water and equals 1 tritium atom in 10^{18} hydrogen atoms or one decay per second or approximately 3.19 pCi/L.)

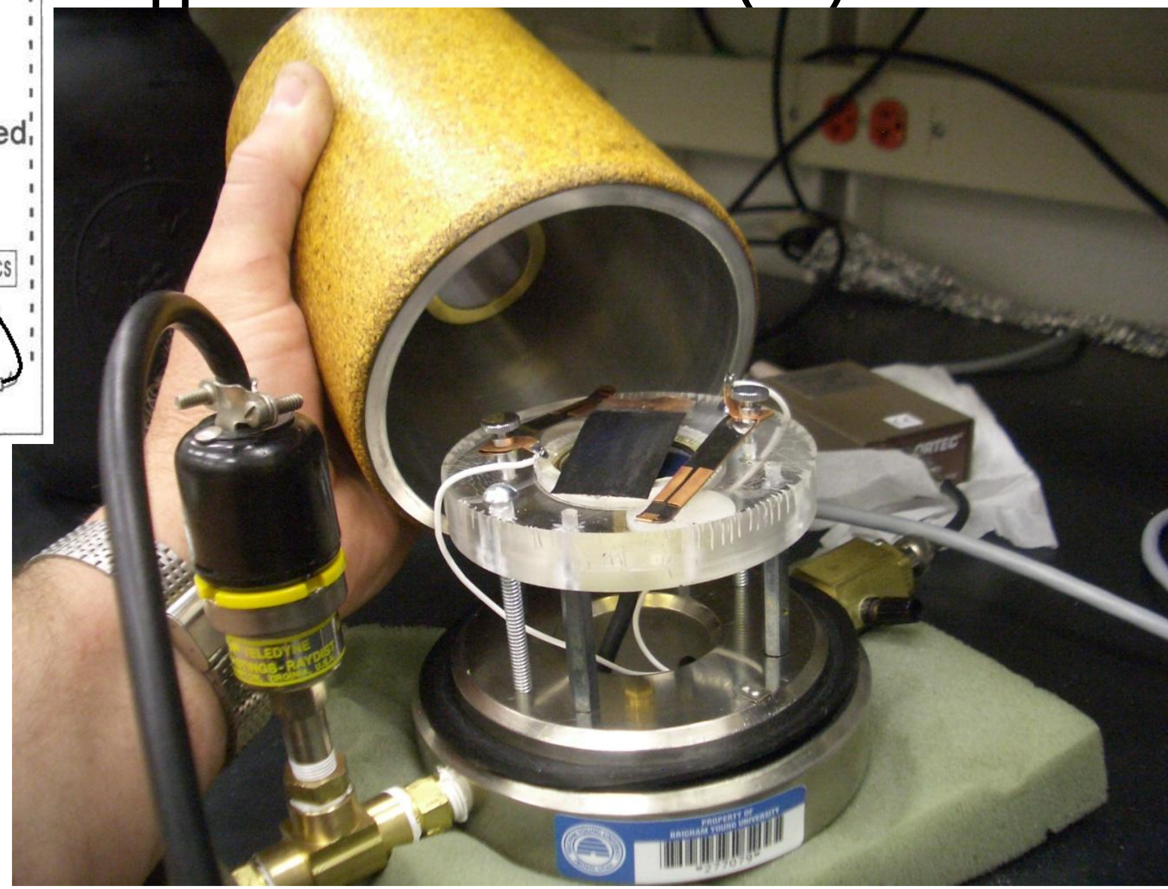

EXIT

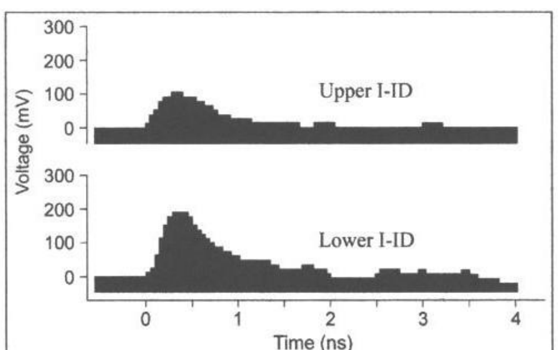
THIRD EXPERIMENTAL TECHNIQUE

Coincident Charged-Particle Detector Using Ion-Implanted Silicon Detectors



Coincident charged particle detector apparatus with two silicon (I-ID) detectors

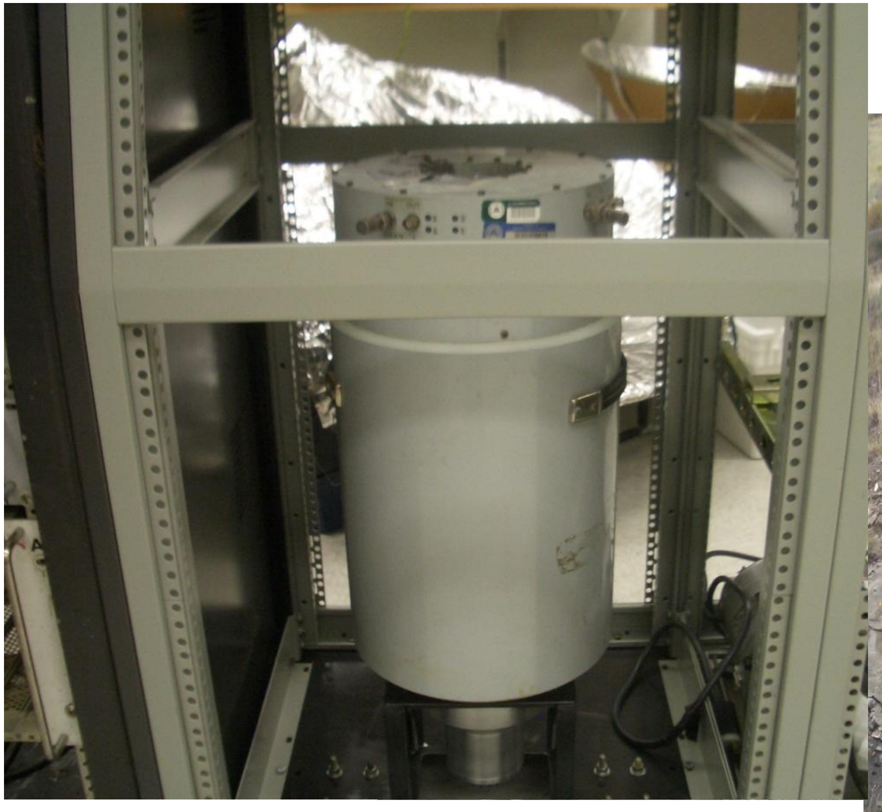




One fusion per 10^{22} d per second = Star in a Jar

F.W. Keeney, S.E. Jones, A.C. Johnson, P.L. Hagelstein, G. Hubler, D.B. Buehler, F.E. Cecil, M.R. Scott, and J.E. Ellsworth, "Charged-particle emissions from deuterated metals," Condensed Matter Nuclear Science, 2005, London: World Scientific, p. 509.

Underground low background neutron well detector



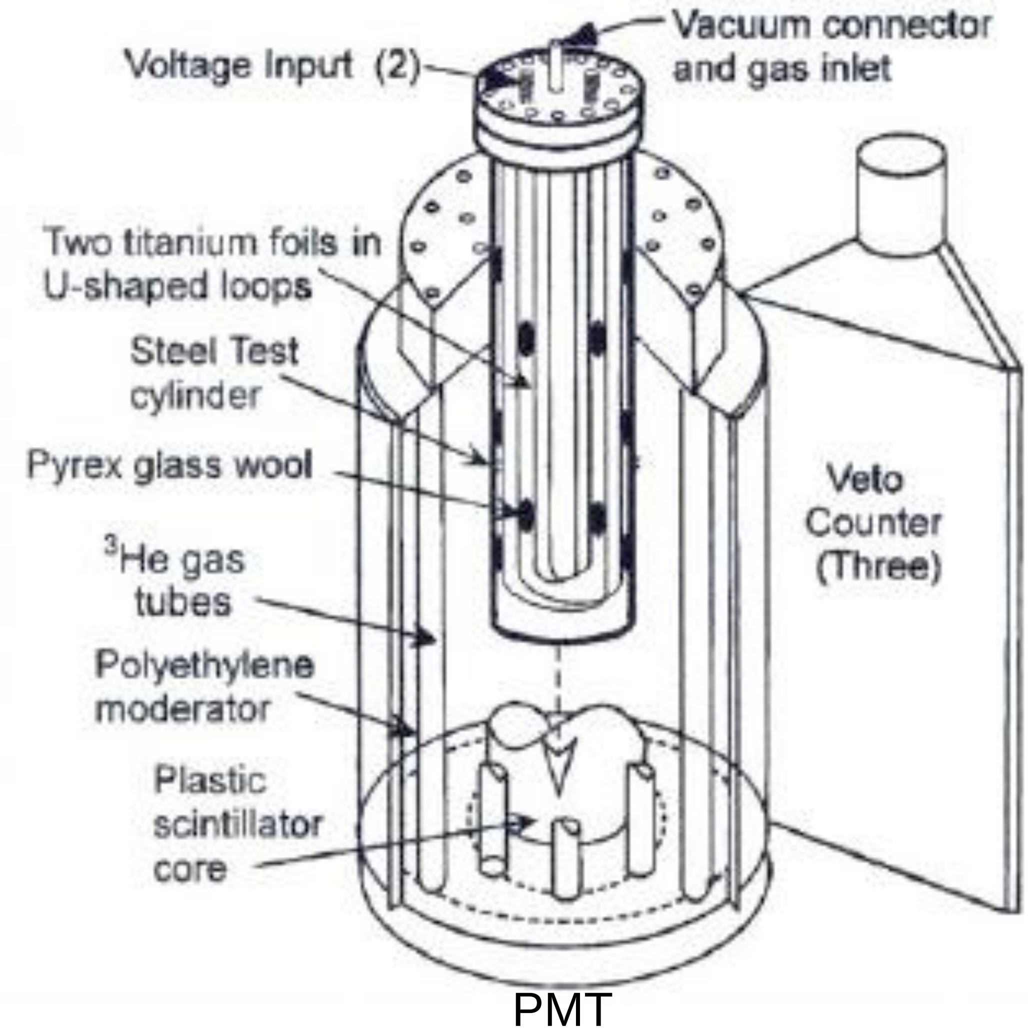
Developed by Howard Menlove and colleagues (Los Alamos National Laboratory) and built by JOMAR Corp.

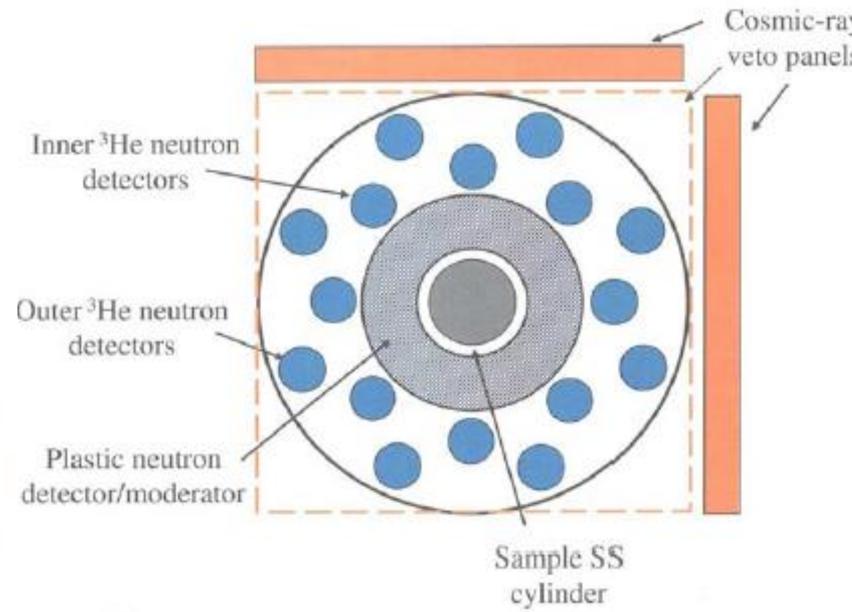
Tunnel, Provo Canyon, Utah

Most sensitive neutron detector, second only to the Kamiokande neutrino detector, which was also used.

-------------------------- FIRST EXPERIMENTAL TECHNIQUE --------------------------

Neutron Emissions from Metal Deuterides



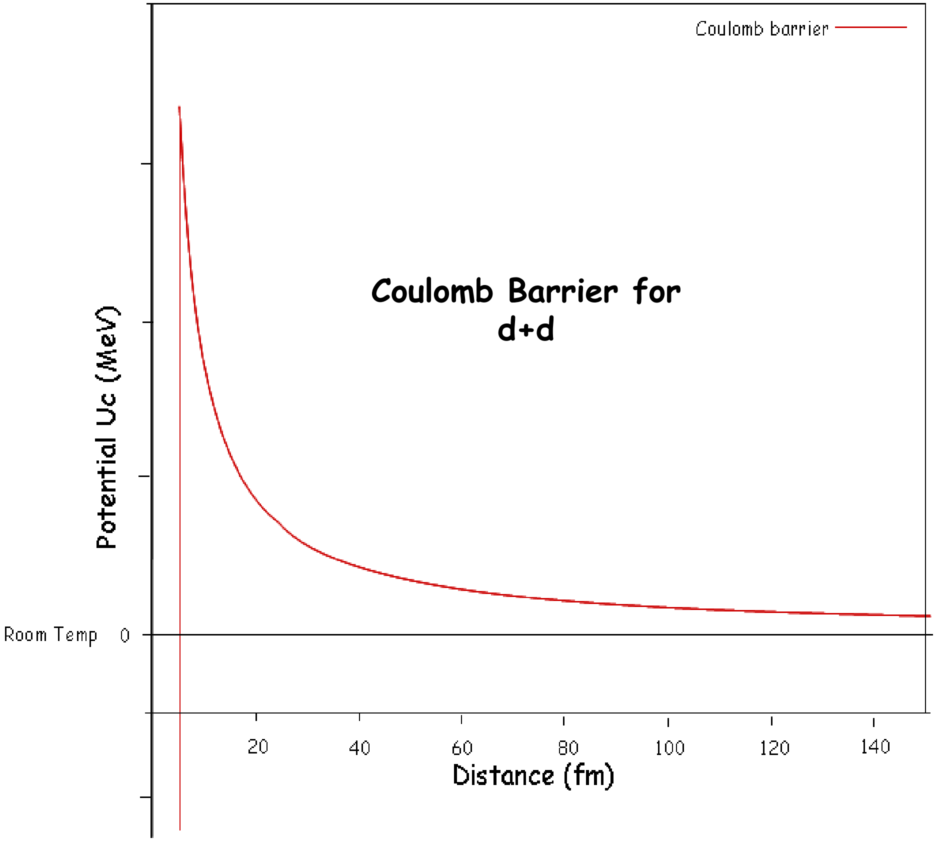


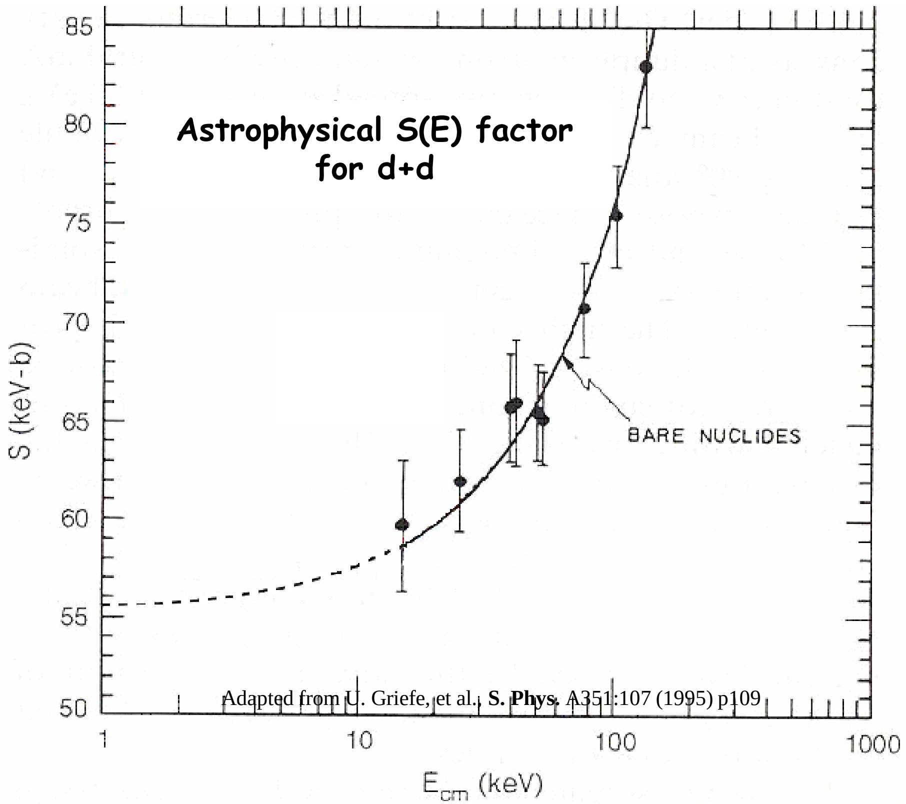
Prep: Ti foils and chamber are out gassed and purged by repeatedly evacuating and filling to 1 atm of H_2 or D_2 while electrically heating Ti foils.

Test run: Chamber pressurized w/ H_2 or D_2 to 40 psi. The chamber is then sealed and Ti foils heated. Reduction in pressure is observed as foils absorb gas.

H.O. Menlove, M.M. Fowler, E. Garcia, A. Mayer, M.C. Miller, R.R. Ryan and S.E. Jones, *Measurement of Neutron Emission from Ti and Pd in pressurized D2 Gas and D2O Electrolysis Cells,* J. Fusion Energy 9(1990): 495-506.

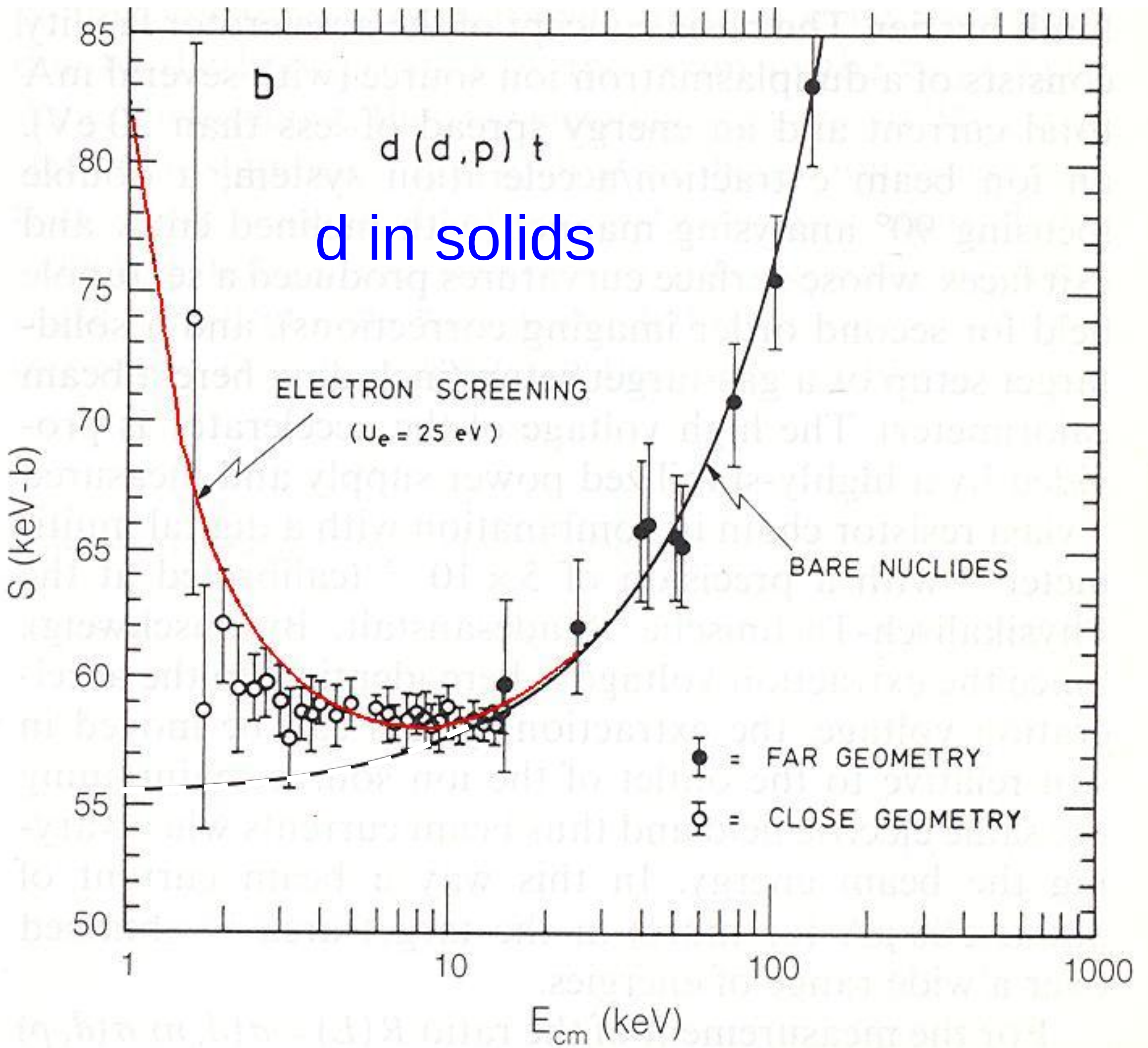
Laboratory Nuclear Astrophysics





Adapted from U. Griefe, et al., **S. Phys.** A351:107 (1995) p109

Fusion enhancement factor, d-beam studies



"…explain the small neutron production rates observed in the … experiment of Jones." .

K. Czerski, et al., Europhys. Lett. 54:449 (2001) p455.

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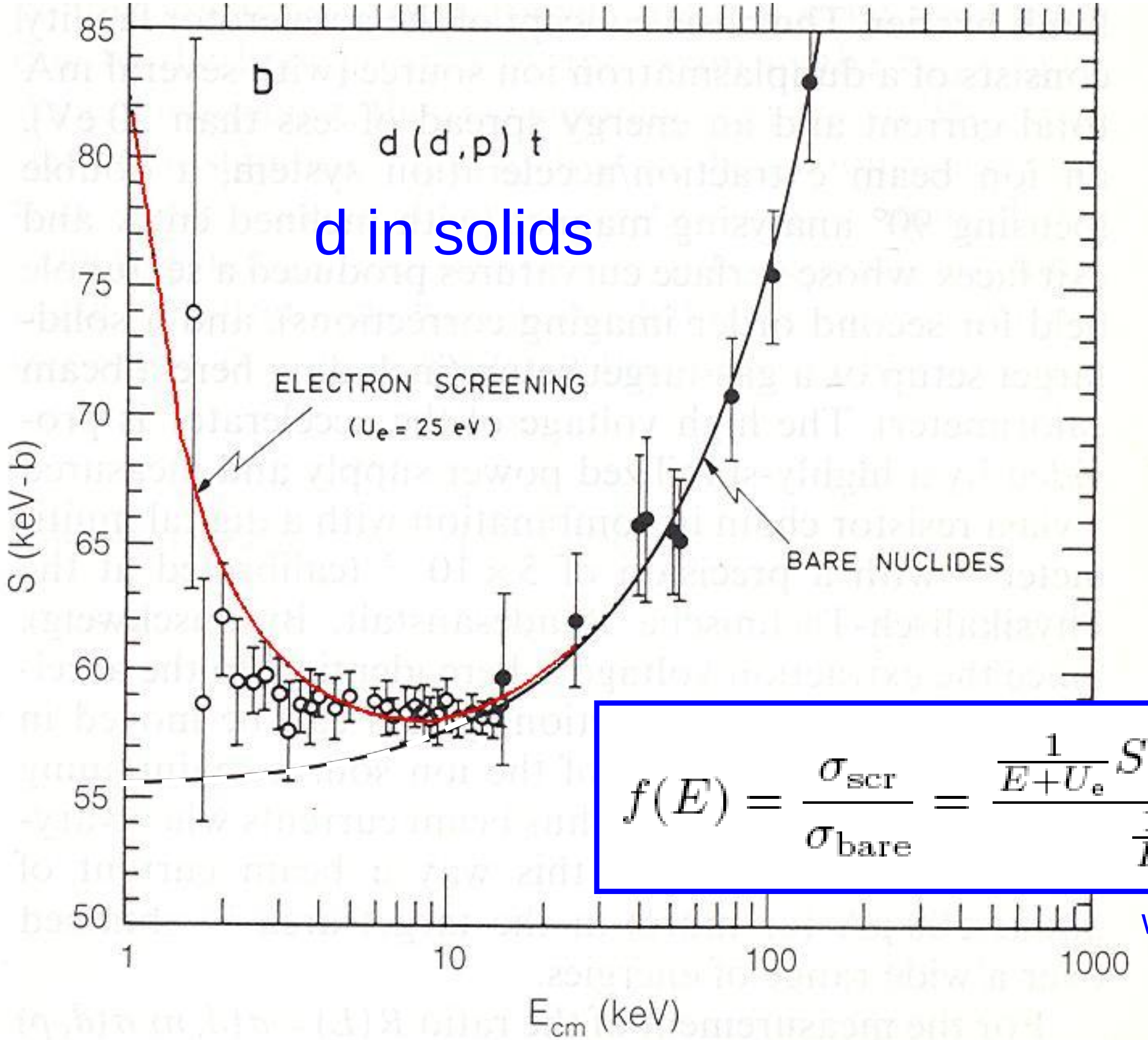


"…explain the small neutron production rates observed in the … experiment of Jones." .

K. Czerski, et al., Europhys. Lett. 54:449 (2001) p455.

$$f(E) = \frac{\sigma_{\rm scr}}{\sigma_{\rm bare}} = \frac{\frac{1}{E+U_{\rm e}} S(E+U_{\rm e}) e^{-2\pi\eta(E+U_{\rm e})}}{\frac{1}{E} S(E) e^{-2\pi\eta(E)}}$$

where U_e is the screening potential

Adapted from U. Griefe, et al., **S. Phys.** A351:107 (1995) p109

LUNA (Laboratory Underground for Nuclear Astrophysics), Gran Sasso Laboratory, Italian Alps

http://www.oufusion.org.uk/newsspring05/fusionnewsspring05.htm

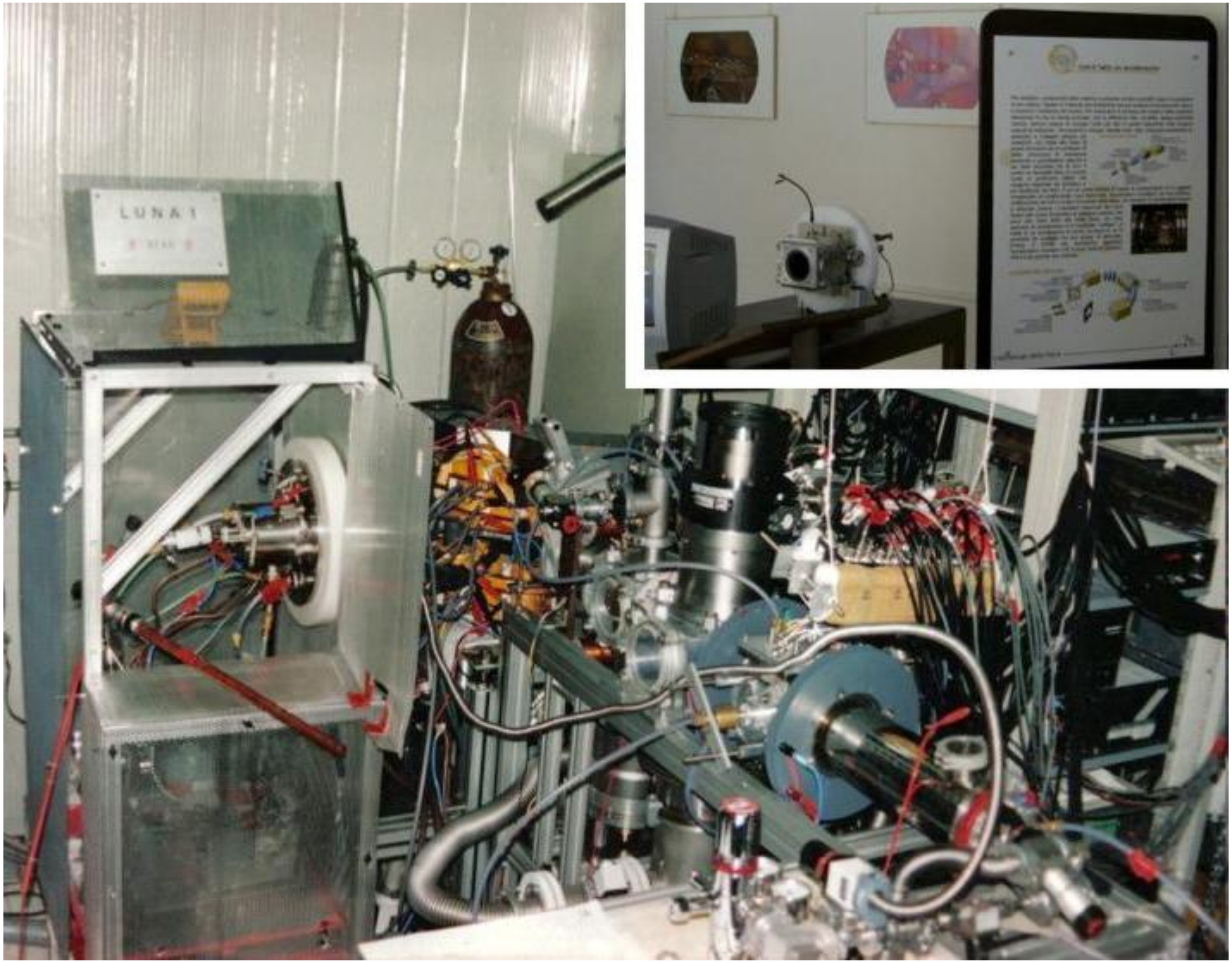

LUNA 1

Table of Empirical Screening Potentials U_e

Material[4]	U_e (eV)	Material[4]	U_e (eV)	Material[4]	U_e(eV)	Material[4]	U_e(eV)
D_2 gas[1]	25 ± 5	Mo	420±50	Sc	≤30	Ho	≤70
Pd	800±90	Mn	390±50	Ti	≤30	Er	≤50
Sb	720±70	Ni	380±40	Y	≤70	Tm	≤70
Pt	670±50	Cd	360±40	Zr	≤40	Yb	≤40
Co	640±70	Ag	330±40	Lu	≤40	BeO	≤30
Au/Pd/PdO[2]	601±23	Ta[3,4]	322±15	Hf	≤30	B	≤30
Tl	550±90	Cr	320±70	La	≤60	Al_2O_3	≤30
Bi	530±60	Pd[3]	280±30	Ce	≤30	CaO_2	≤50
Al	520±50	Au	280±50	Pr	≤70		
In	520±50	Ta	270±30	Nd	≤30		
Ba	490±70	W	250±30	Sm	≤30		
V	480±60	Rh	230±40	C	≤60		
Pb	480±50	Re	230±30	Si	≤60		
Zn	480±50	Ru	215±30	Ge	≤80		
Cu	470±50	Sr	210±30	Eu	≤50		
Nb	470±60	Ir	200±40	Gd	≤50		
Fe	460±60	Be	180±40	Tb	≤30		
Mg	440±40	Sn	130±20	Dy	≤30		

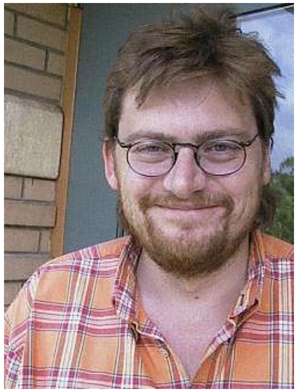
Material[5]	**U_e (eV)**
Pd-Li	**1500±310**
Au-Li	**60±150**
Li metal	**?**

Yet to be published 3500eV for *a cleaned* target

1. U. Griefe, *et al.*, **Z. Phys.** A351:107 (1995).
2. H. Yuki, J. Kasagi, A.G. Lipson, *et al.*, **JETP Letters**, 68:823 (1998).
3. K. Czerski, *et al.*, **Europhys. Lett.** 54:449 (2001).
4. F. Raiola, *et al.*, **Eur. Phys. J.** A19:283 (2004).
5. J. Kasagi, *et al.*, **J. Phys. Soc. Japan**, **73**:608 (2004).

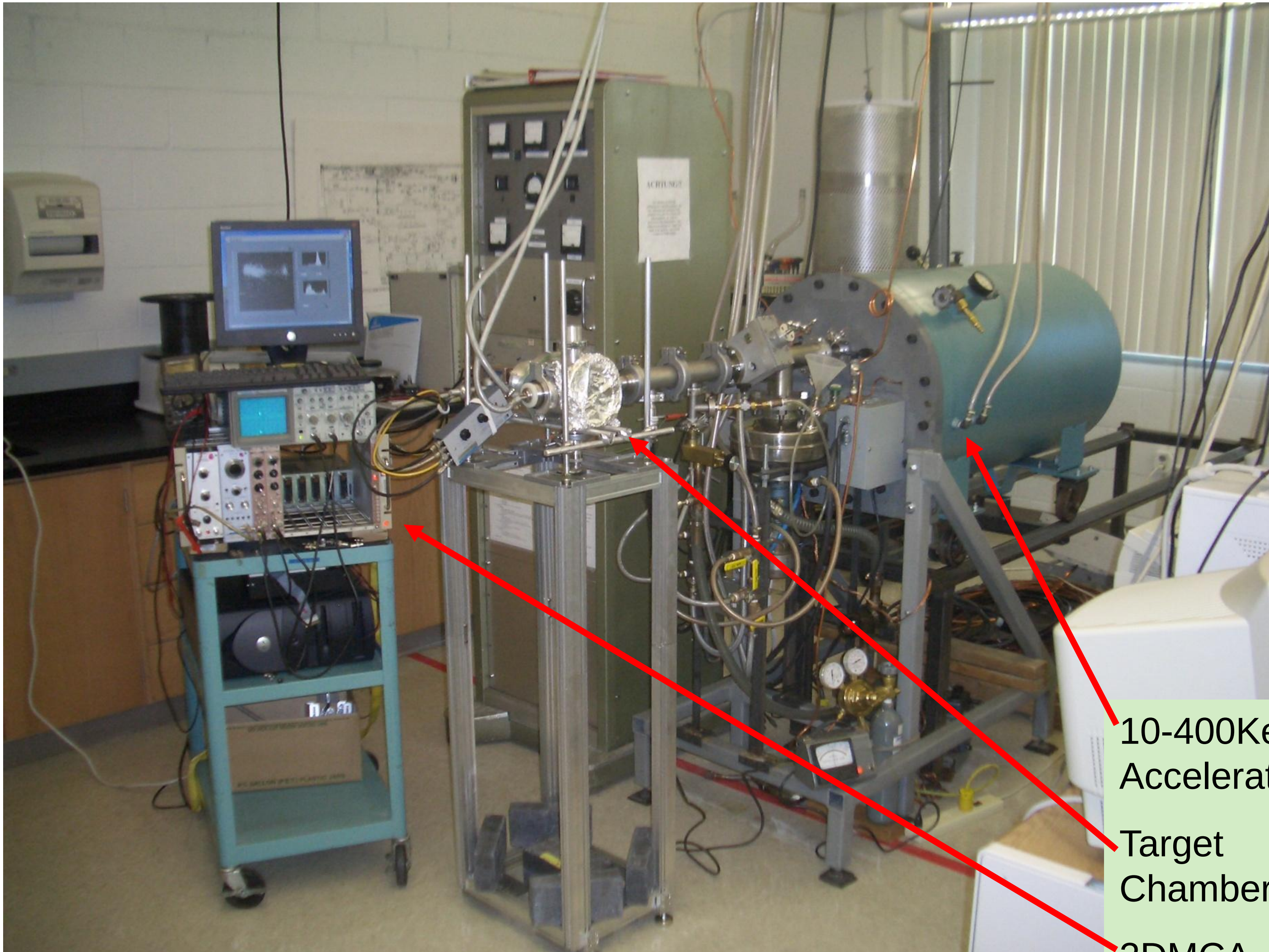
"The cross sections of d(d,p)t at E < 10keV show clear evidence for electron screening effects. However, the observed cross section enhancement is significantly larger than can be accounted for from available atomic physics models."

U. Greife, et. Al. Z. Phys. A 351, 107-112 (1995)



Associate Professor, Colorado School of Mines.
Associate Professor. Diplom-Physiker Westfaelische Wilhelms-Universitaet Muenster, Germany;
Dr. rer. nat. Ruhr-Universitaet Bochum, Germany

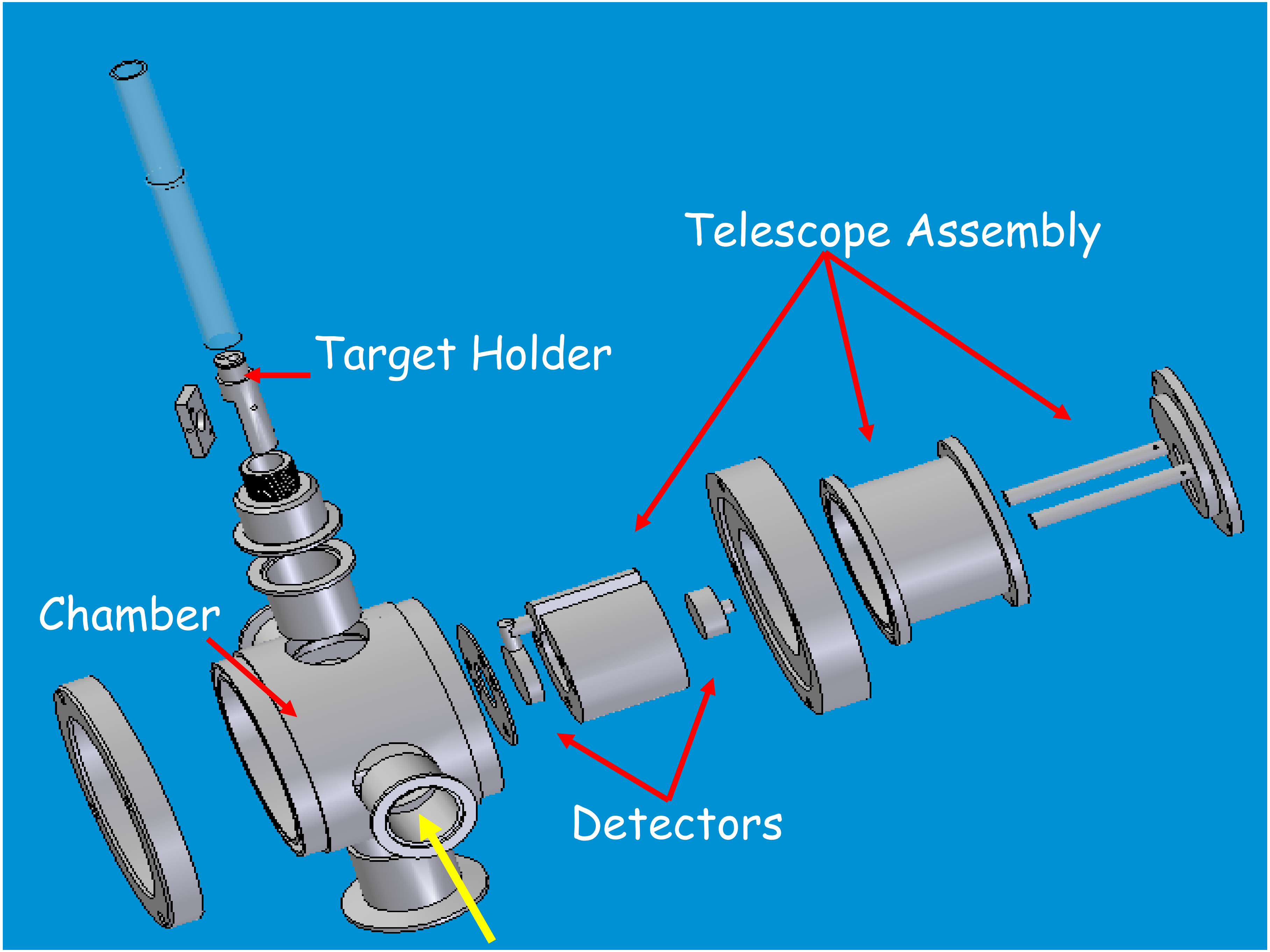
BYU d-beam target and analyzer facility, under construction

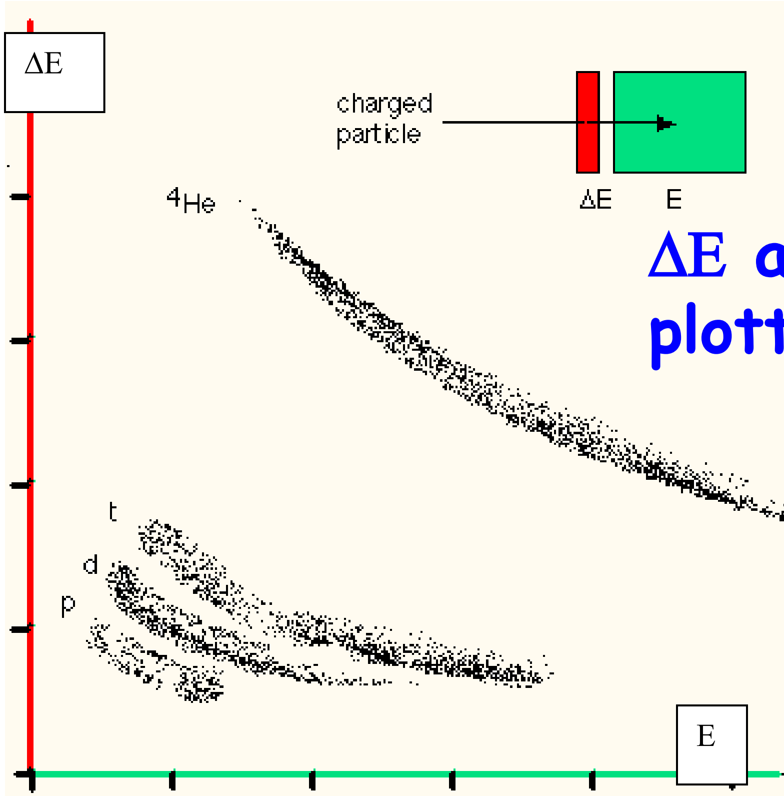


10-400KeV Accelerator

Target Chamber

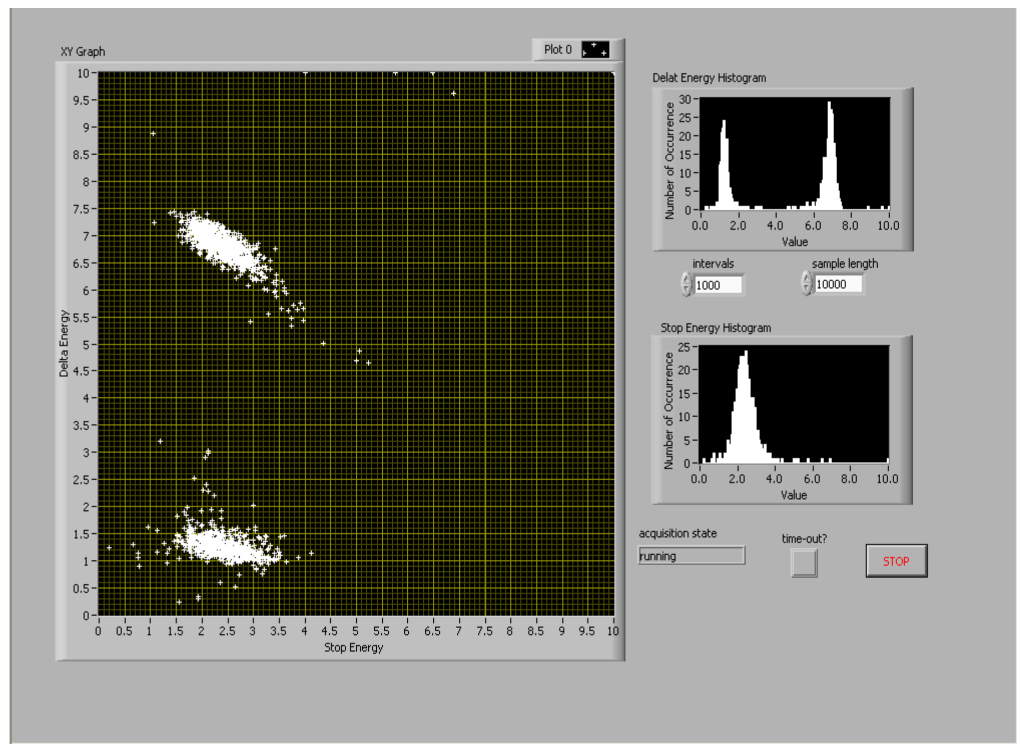
2DMCA


Telescope Assembly
Target Holder
Chamber
Detectors

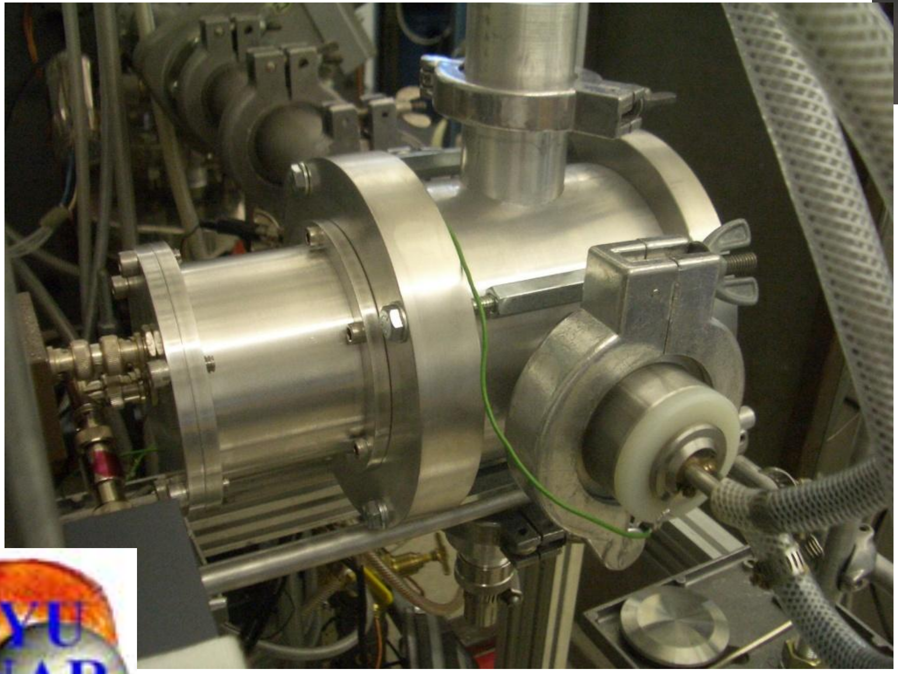


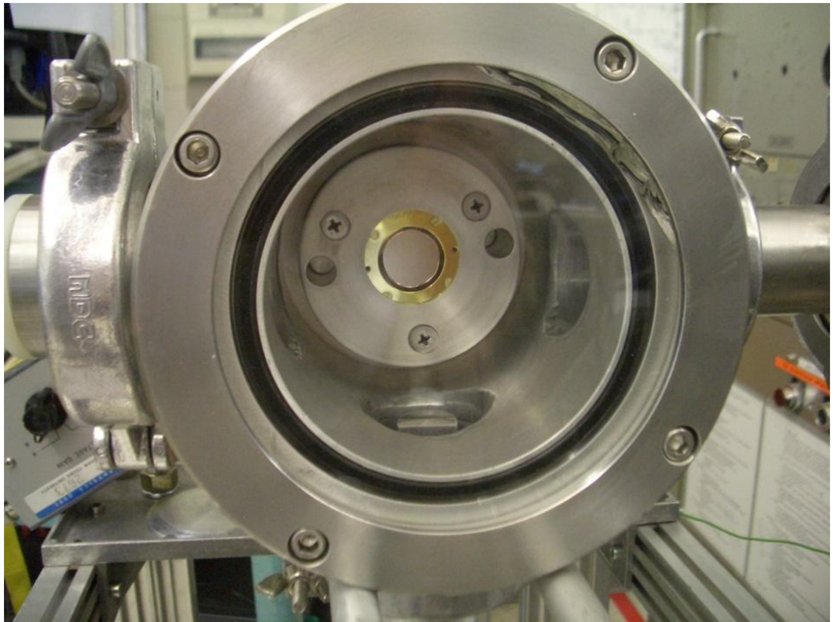
ΔE and E stop detectors plotted in two dimensions

Tested with Americium-241 5.64 MeV alpha source and 2.15 MeV protons scattered from a 24um tungsten wire.

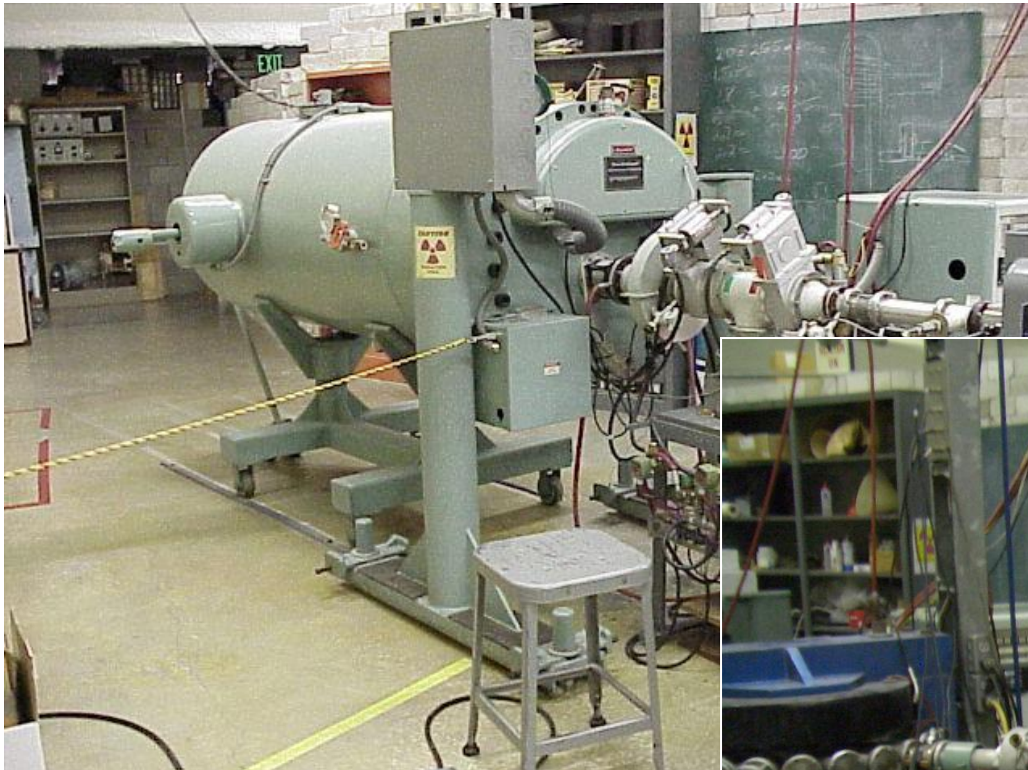


Target Chamber Assembly

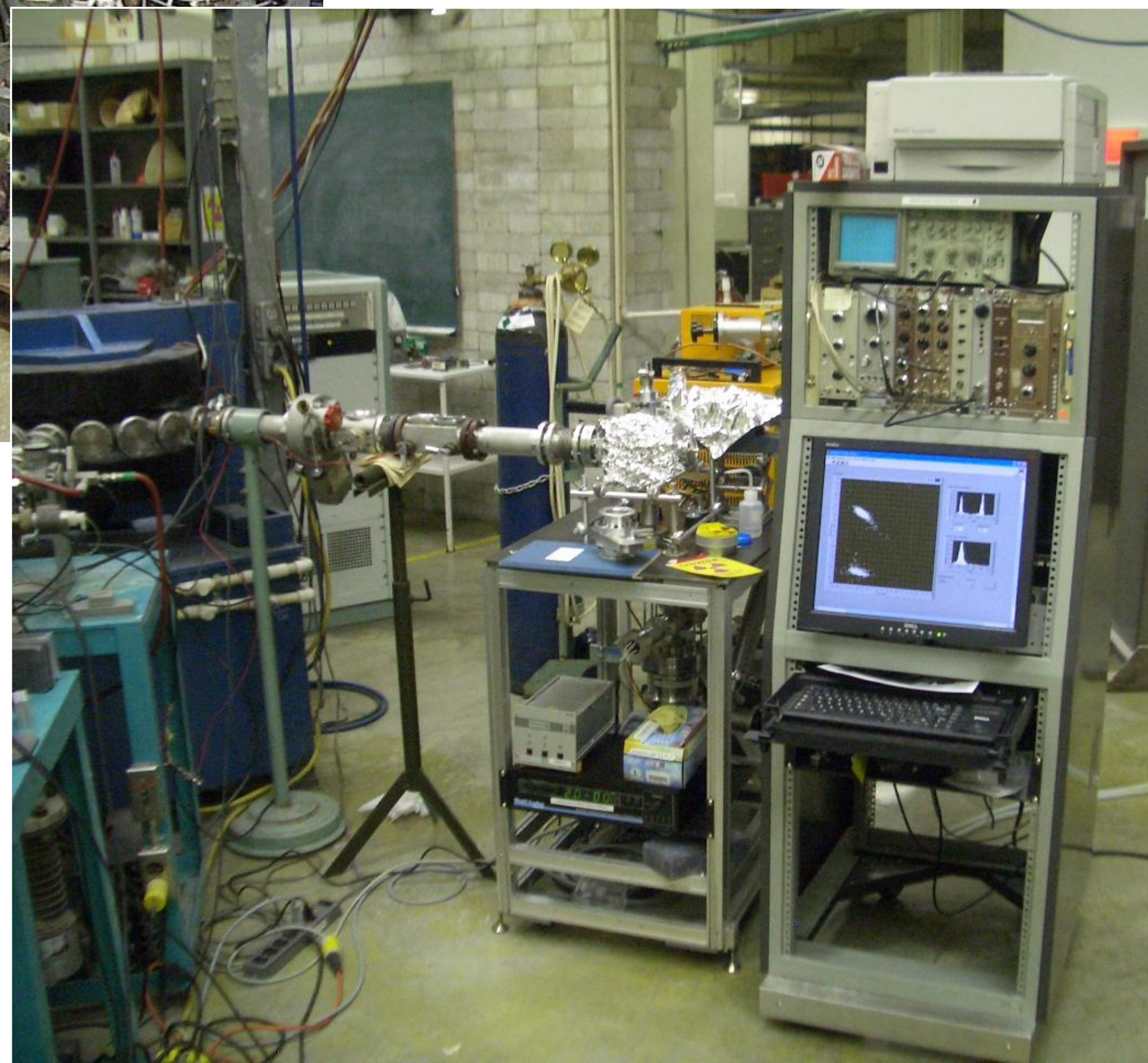




BYU
LNAR

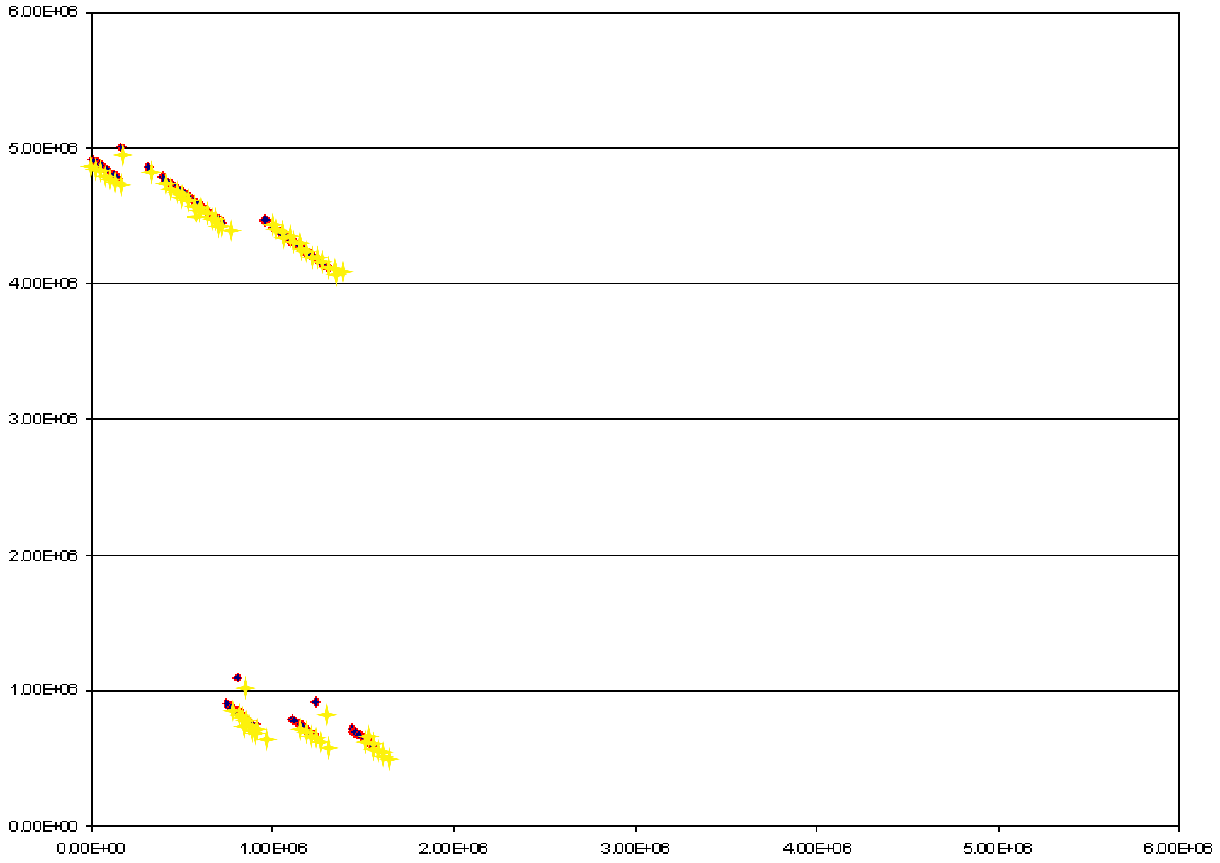


PIXE 2MeV Accelerator



Charged particle spectrometer under test

Monte Carlo Simulation of protons (1.56, 1.90, 2.15MeV) and alphas (4.92, 5.17, 5.42MeV)



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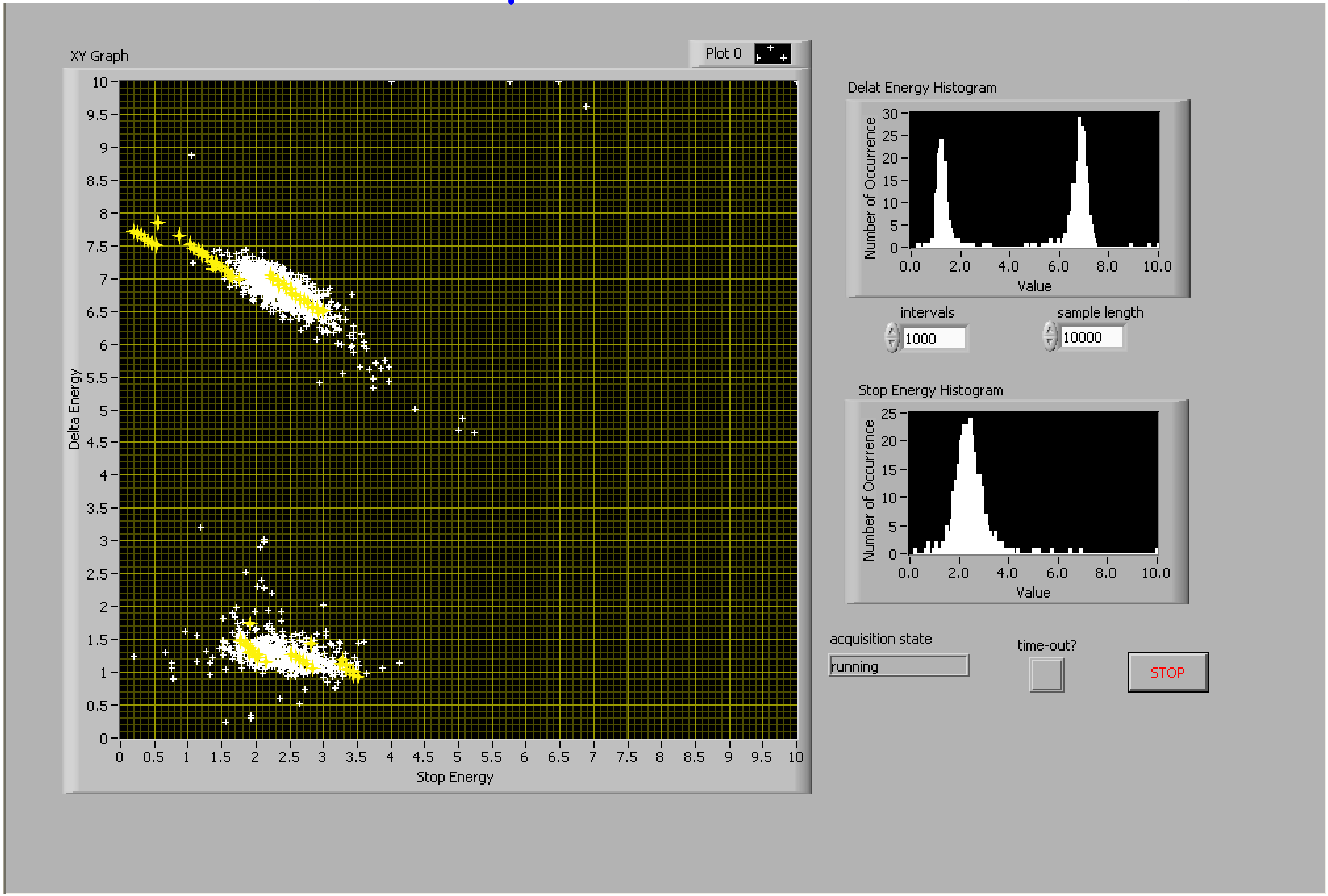
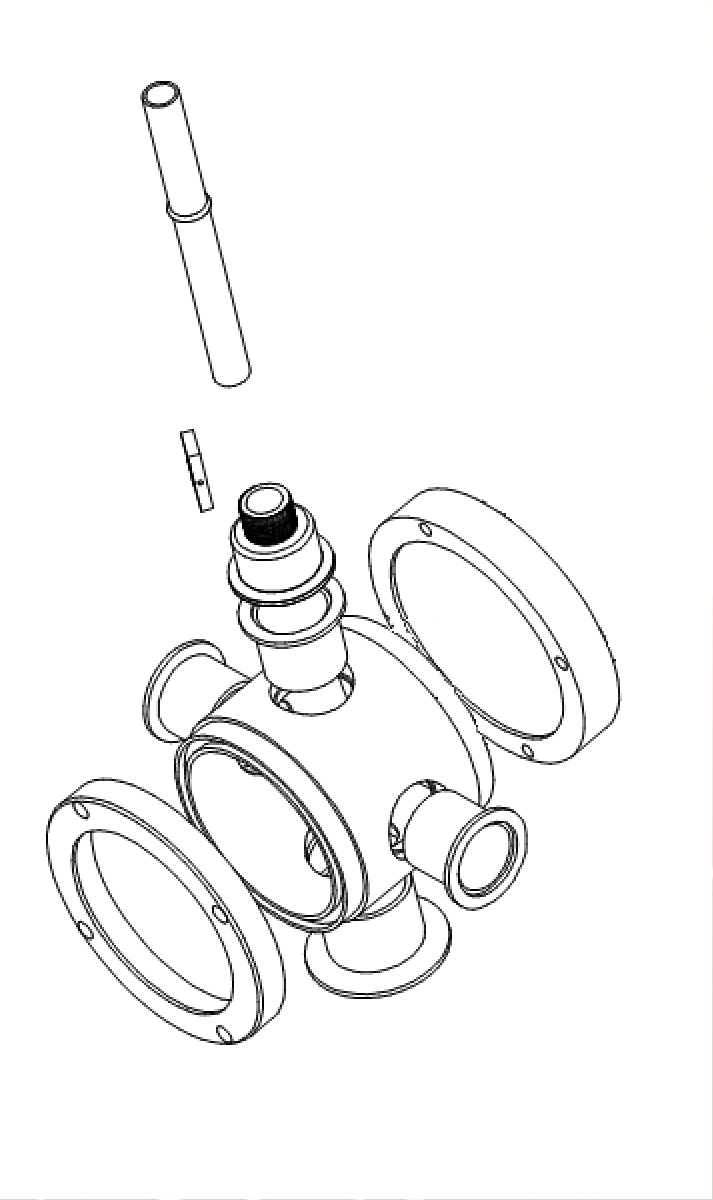
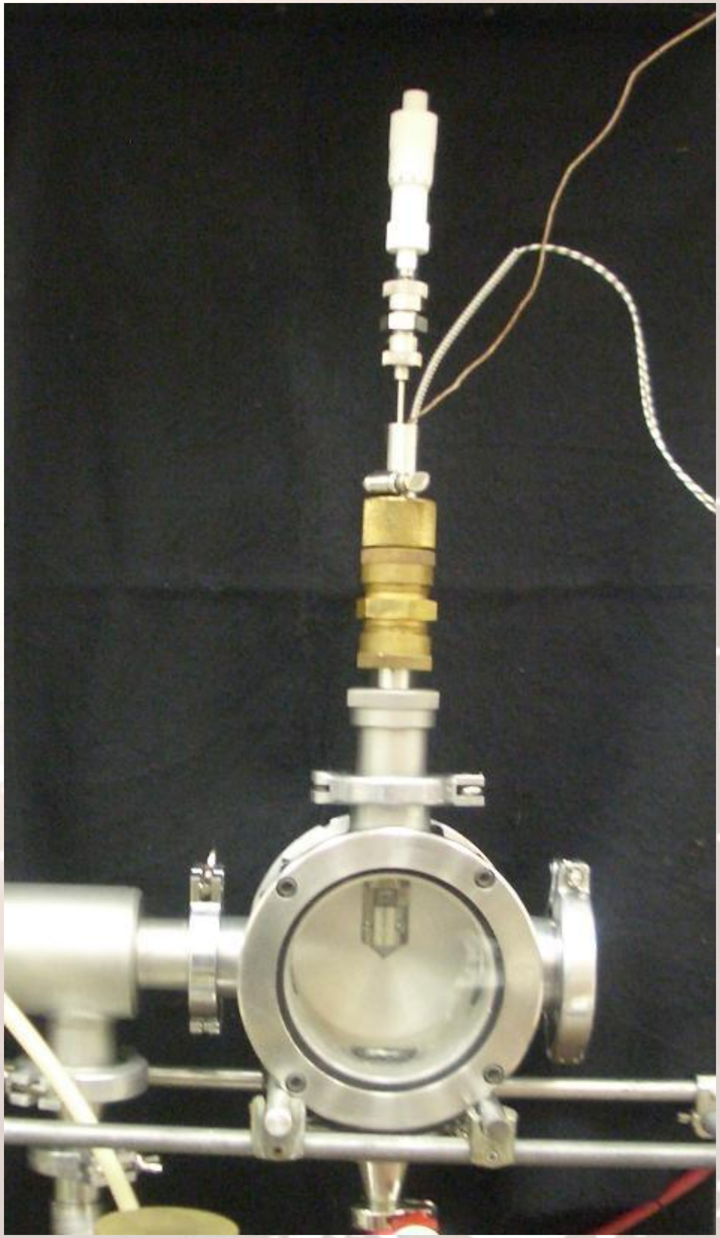
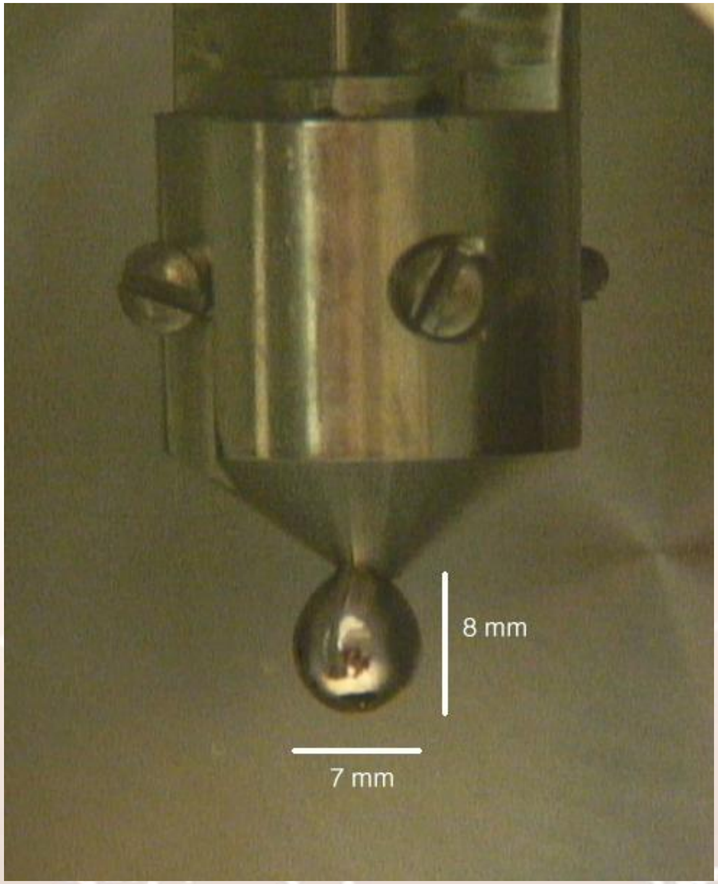


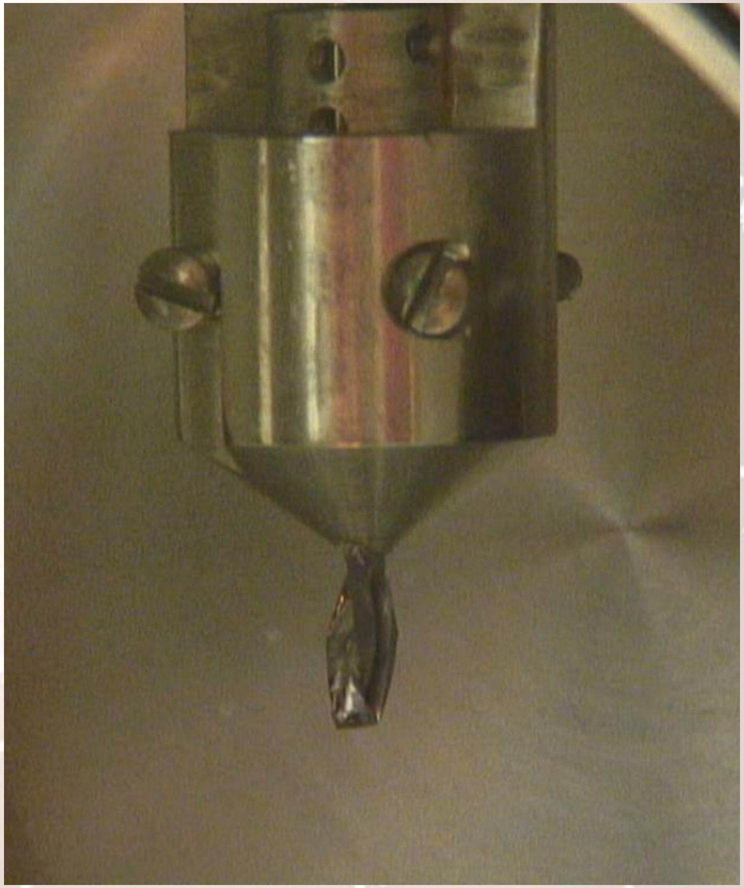
Liquid Lithium Target Chamber Assembly





Liquid lithium pendent

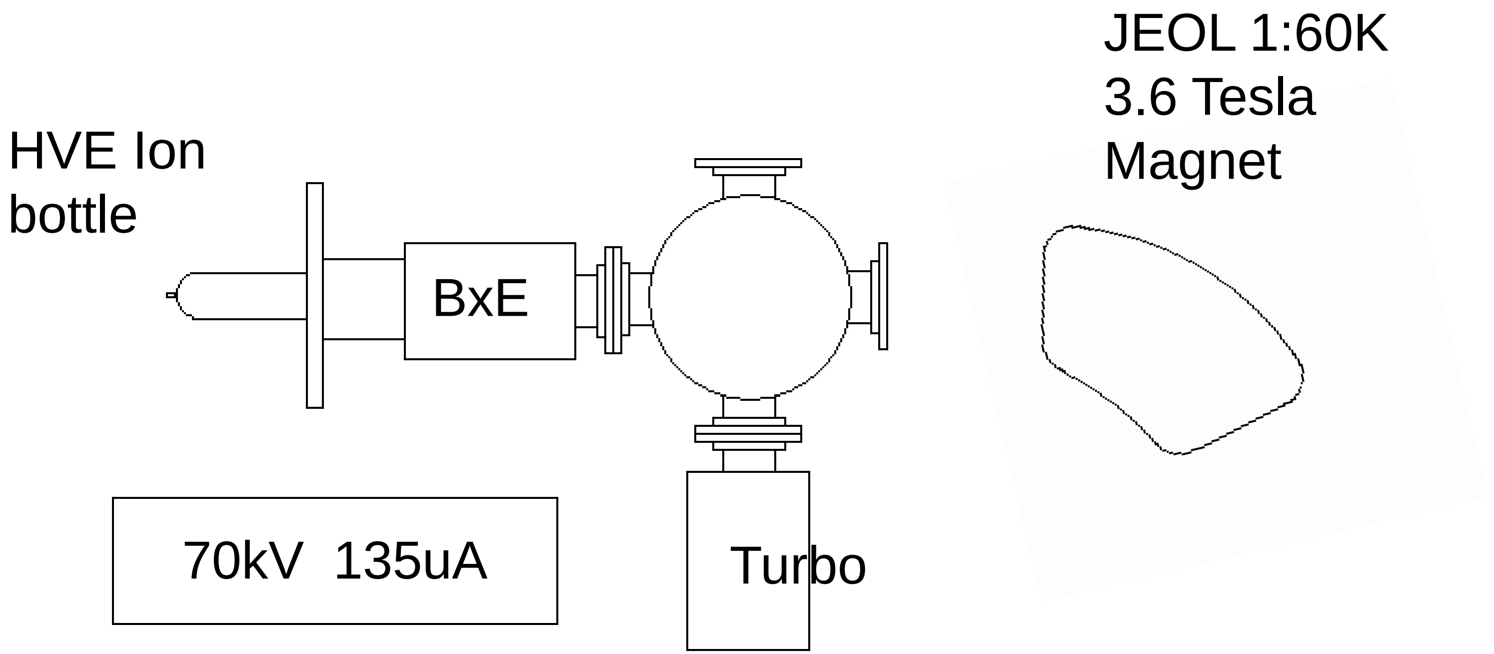




2MeV HVE AN2000 circa 1965

- Moved, building remodeled
- Flood – treated circulated chilled

Experience for students:



Develop short beam path accelerator
New neutron spectrometer
Updated charge particle spectrometer

Laboratory Nuclear Astrophysics

Studying fusion reactions at characteristically low energies is needed to understand stellar processes and may be a key to understanding primordial formation, nucleosynthesis of the elements, and may give clues to fusion energy technology.

Rolfs, Trautvetter and Rodne. **Current status of nuclear astrophysics.** Rep. Prog. Phys. **50 (1987)**

"… is often a frustrating science. The desired cross sections are among the smallest measured…" = *nuke-speak for "it's really hard to see a reaction"*

"… often requiring long data collection times with painstaking attention to background. = *plan on days to weeks*

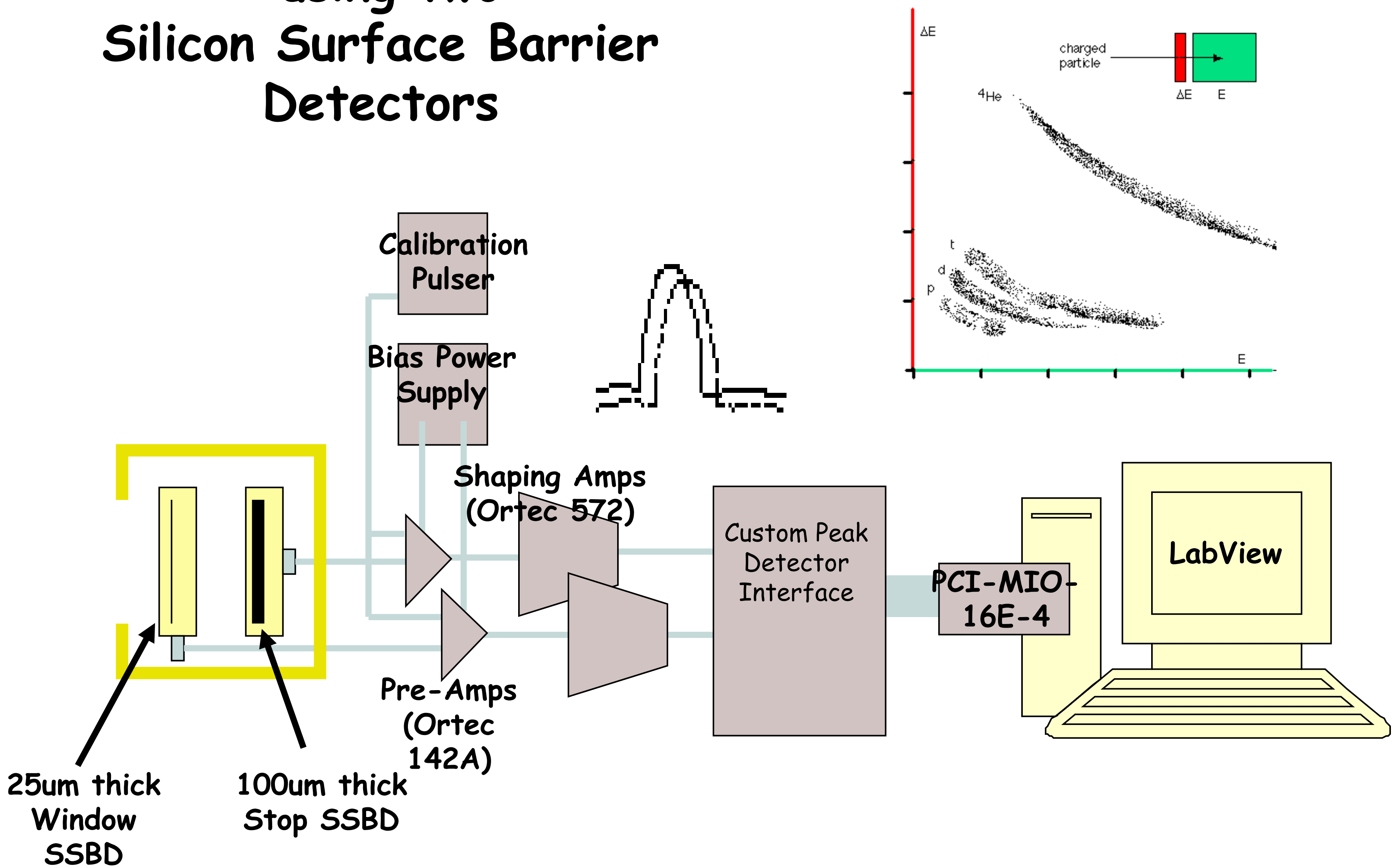
"From a purely nuclear point of view, the reactions studied are often of comparatively little interest." = *not easily funded*

"… has provided unexpected intellectual rewards in nuclear physics itself." = *expect a couple of decades for unexpected results to be taken seriously.*

… requires specialized equipment and environments = *hope you like dark, deep, dripping wet places*

Thank you.

Charged Particle Telescope using two Silicon Surface Barrier Detectors

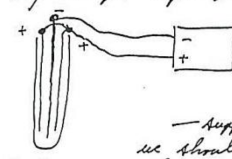


Steven E. Jones (particle physics), J. Bart Czirr (neutron deteciton), Gary L. Jensen (accelerator physics), Daniel L. Decker (condensed matter and dept chairman), and E. Paul Palmer

Steven Jones having exploited muon catalysis to its maximum, Paul Palmer proposed deuterium loading a "mother-earth soup" hoping enough tunneling will occur to be detectable.

… not significant enough to conclude…

May 22 1986 Electrolytic infusion of hydrogen into metals
We constructed an electrolytic cell in a test tube to try to get hydrogen into metals.



Used a solution of HCl in water.
We used copper cathode (−) and nickel anode (+) and ran enough current through to get bubbling at the electrodes.
— supposedly, if Cu behaves like Fe, we should get H in the metal.

After 8-10 hrs, a heavy green coating built up on cathode(−) This flaked off when dry. The cathode was nickel plated underneath in a spotty grey-black silver coating. There was green gelatinous stuff in liquid.

We put this strip which supposedly contained hydrogen and deuterium (in the normal concentration for D of .016 %) around the crystal of a gamma spectrometer. We counted background for 1200 sec and copper strip for about — ~ 2400 sec I believe.

May 22 1986 (cont.) Electrolytic infusion of H.
The results were completely inconclusive. The rate with the hydrated sample was 10% ± 7% greater than background. The count on the background was too short but the equipment was needed for other purposes. As Bart said — you wouldn't bet on cold fusion on the basis of these results — but neither would you bet against it.

We don't know if we had any H in the copper. We are going to weigh it and bake it, but that is of doubtful validity because of oxide formation and surface contamination effects.

May 23, 1986 Electrolytic cell using D_2O.

I rigged up the same cell as before but used 10% D_2O, sulfuric acid, and distilled water with copper anode and cathode. I ran it with 200 mA current and approx 1.5 V across cell. Hydrogen came off the cathode in small bubbles. Ran from ~ 10:00 AM

Bart suggests we use palladium as the metal because we know it has the ability to let H diffuse through it readily. It should work fine.

Ran cell 4½ hrs at 200 mA then cut to 100 mA at 3:00 PM