

Plasma-induced electron screening at the Bragg Peak

ICCF-25

International Conference on Condensed Matter Nuclear Science

27-31 August 2023,
Radisson Blu Hotel, Szczecin, Poland

L. P. Forsley^{1,2,3}, V. Pines^{2,4}, M. Pines^{2,4}, T. L. Benyo² and P. Ugorowski^{2,5}

¹. lawrence.p.forsley@nasa.gov

². NASA Glenn Research Center, Brookpark, OH, USA

³. GEC LLC, Annandale, VA, USA

⁴. PineSci Consulting, Avon Lake, OH, USA

⁵. HX5, Brookpark, OH, USA

Overview



- **Astrophysical and Terrestrial Electron Screening**
- **Stopping Power and the Bragg Peak**
- **Modeling**
- **Boosted Reactions**
- **Conclusions**
- **References**
- **Acknowledgements**

Takeaways

- Electron Screening enhances nuclear reactions
- Screening effective below 10 keV kinetic energy
- Linear Energy Transfer (LET) produces plasma screening
- Plasma screening maximum near LET Bragg Peak
- MeV reaction products slow by $LET < 10 \text{ keV}$
- Cold deuteron heating by neutrons and screened charged particles increase nuclear reaction rates

1. Astrophysics

- Strong and Weak Screening:
Salpeter, 1954
- *Astrophysical Reaction Rates*
Hagino, 2002
- White dwarf stars and giant planets
 - Fermi-Degenerate $10^{23}/\text{cm}^3$

2. Laboratory Astrophysics

- Accelerator Studies
Rolf, Czerski, Huke et al., 1980s
Bystrisky, Kitamura, 2000s
- Gamow Factor Enhancement
Pines, 2020

3. Terrestrial

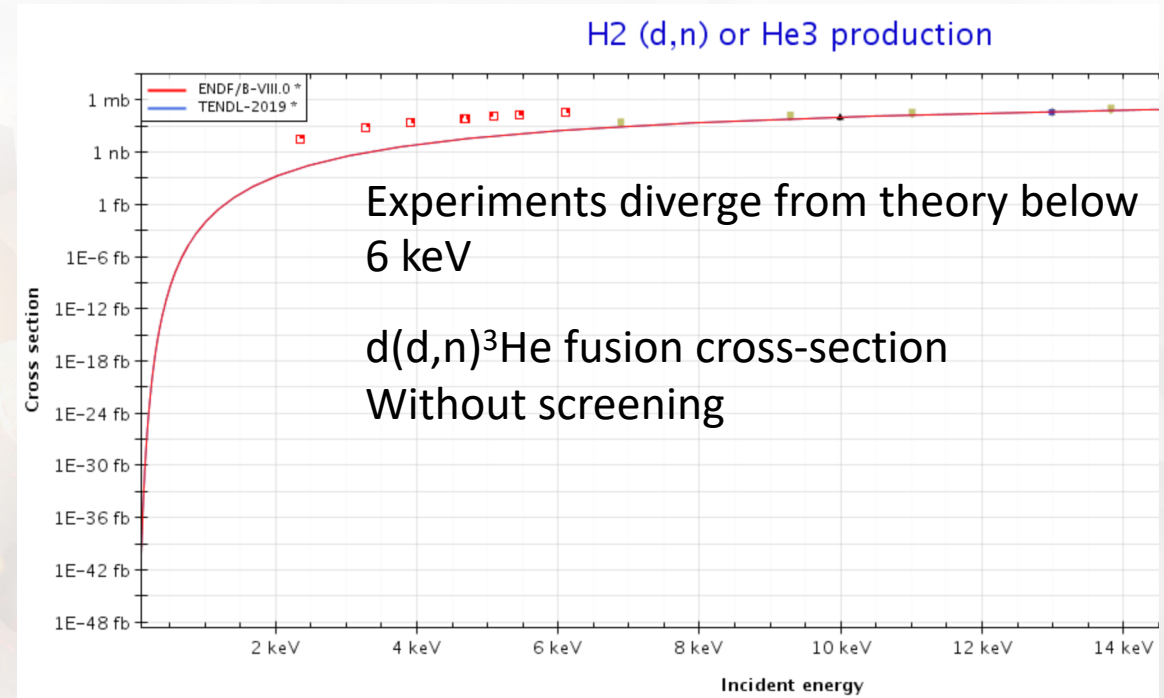
- Metal Conduction bands, ICF

4. Solid State Fusion/LENR/LCF

- Srinivasen, 1991
- Schenkel, 2019

Electron Screening

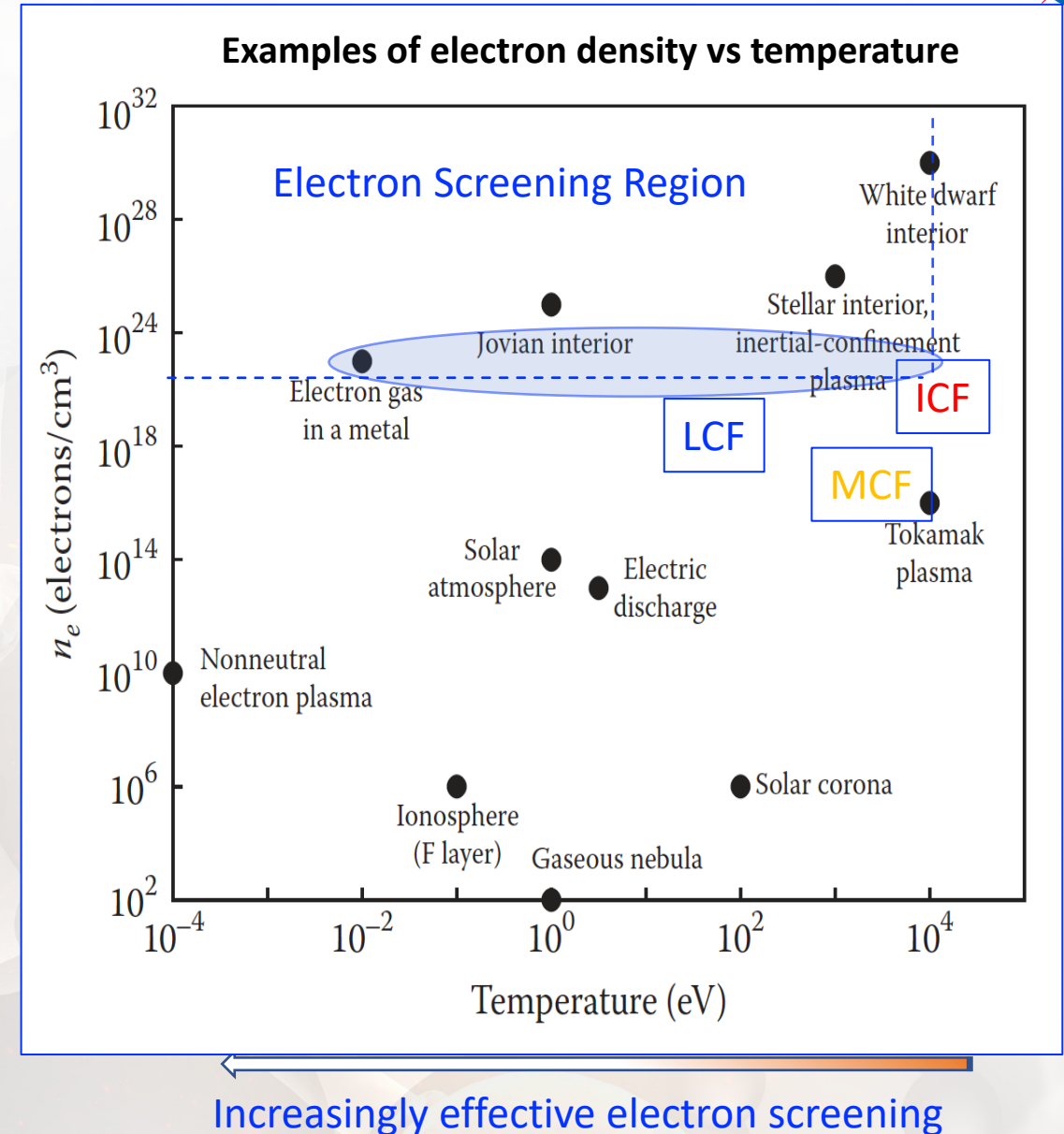
However



Limited data below 5 keV

Electron Screening Across the Board

- Fermi Degeneracy occurs with $> 10^{23}$ electrons/cm³ :
 - White Dwarf stars
 - Gas giant planets
 - Metal conduction bands
 - Hydrided and Deuterated lattices
- Fermi Degeneracy is relatively temperature insensitive
- LBNL results (*Nature* and *Journal of Applied Physics*) attribute a **100-fold+ increase in fusion rates to electron screening as low as 1.2 keV cm.**
- **LCF Straddles both hot fusion and electron screened regimes.**



Electron Screening



Overcoming the Coulomb Barrier in Nuclear Reactions

- Three types
 - Lattice or Conduction electrons
 - Plasma screening by hot electrons
 - Atomic shell (bound) electrons

Condensed Matter has the advantage of maintaining a cold plasma with Fermi-degenerate electrons and ions at densities $\sim 10^{23}/\text{cm}^3$ as contrasted by a tokamak plasma with $10^{14}/\text{cm}^3$ ions and electrons.

Electron screening results in a *more transparent Coulomb Barrier, shifting the Gamow Factor*, as if deuterons were at far higher energies.

Laboratory astrophysics using accelerated deuteron beams show lattice and plasma screening provide up to 3+ keV screening.

Screened ions have a higher large angle scattering probability resulting in higher nuclear reaction rates by increasing the astrophysical factor $S(E)$.¹

This exponentially increases fusion rates.

Stopping power and the Bragg Peak

S is the stopping power described by Bethe-Bloch formula¹: $\frac{-dE}{dx} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$

It is very high for heavy-charged ions with very short ranges:

e.g. 5 MeV alpha stops in 20 μm aluminum alloy.

T is the kinetic energy of the charged particle,

n_{ion} = number of electron-ion pairs formed per unit path length,

I denotes the average energy needed to ionize an atom in the medium.

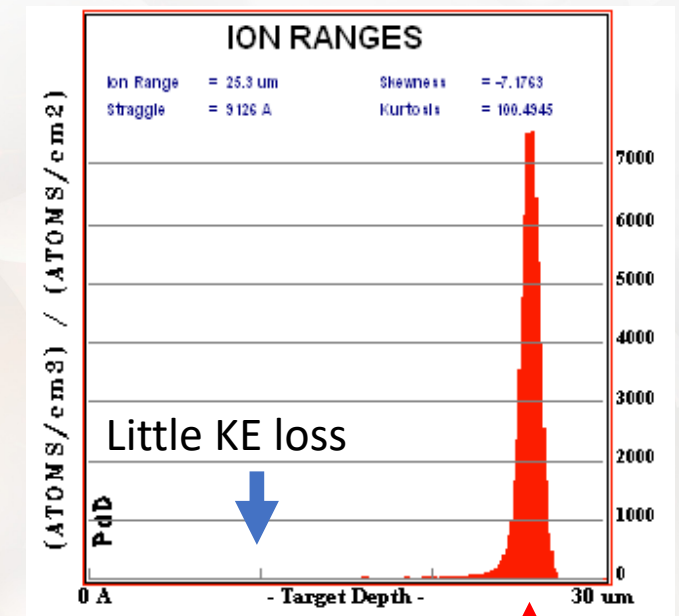
S increases as the particle velocity decreases. ²

$$S(T) = -\frac{dT}{dx} = n_{ion} \bar{I},$$

The charged particle essentially stops at its Bragg Peak

3 MeV fusion proton stops in 25 μm

D(d,p)T 3 MeV Proton in PdD



Bragg Peak

¹. https://hallaweb.jlab.org/12GeV/experiment/E12-07-108/Weekly_meetings/12Oct2015/thir_12/Ioni_energy_loss.pdf

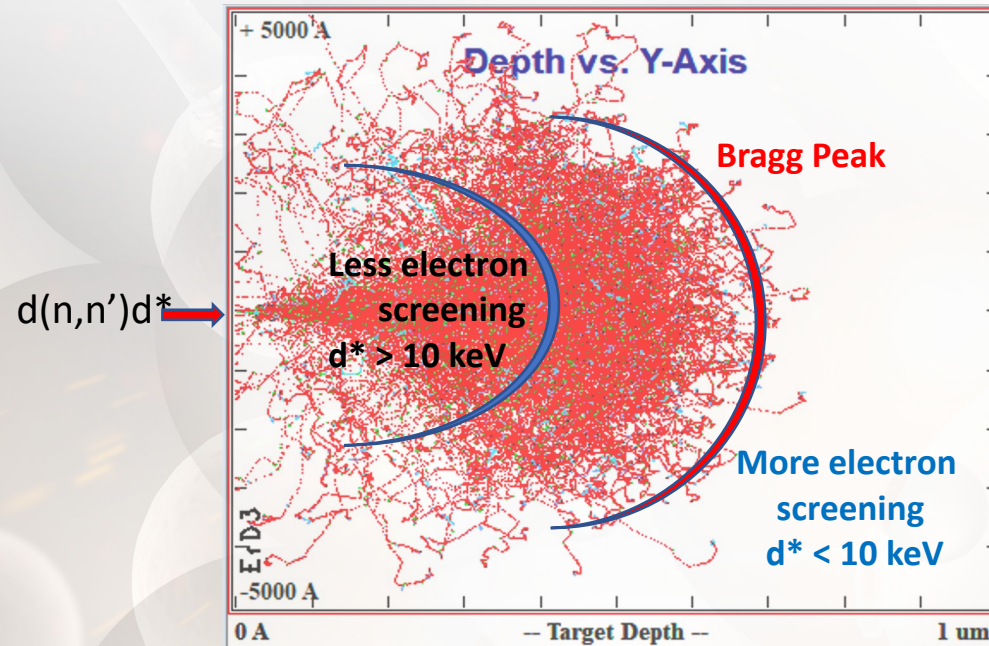
². <https://www.nuclear-power.com/nuclear-power/reactor-physics/interaction-radiation-matter/interaction-heavy-charged-particles/stopping-power-bethe-formula/>

Modeling Plasma and Lattice Screening Coming to the Bragg Peak

SRIM/TRIM¹ Ion Transport in Matter

Model of 64 keV d* Ions slowing in ErD₃ Lattice

10³ particles tracked



Calculation Parameters		
Backscattered Ions		22
Transmitted Ions		0
Vacancies/Ion		29.9
ION STATS		
	Range	Straggle
Longitudinal	4358 A	1315 A
Lateral Proj.	1392 A	1707 A
Radial	2197 A	1061 A

d* ion loses energy by ionizing lattice atoms producing free electrons.

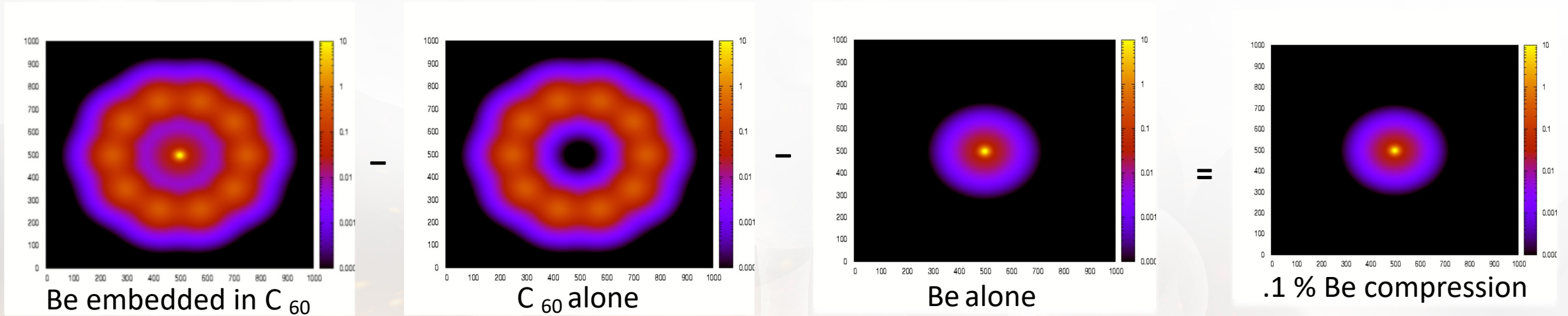
Free electrons increase plasma screening.

When d* energy drops below 10 keV electron screening predominates.

Eventually all 64 keV d slow by Linear Energy Transfer (LET) to below 10 keV.*

Except when nuclear interactions occur.

Breakdown of the Born-Oppenheimer Approximation¹



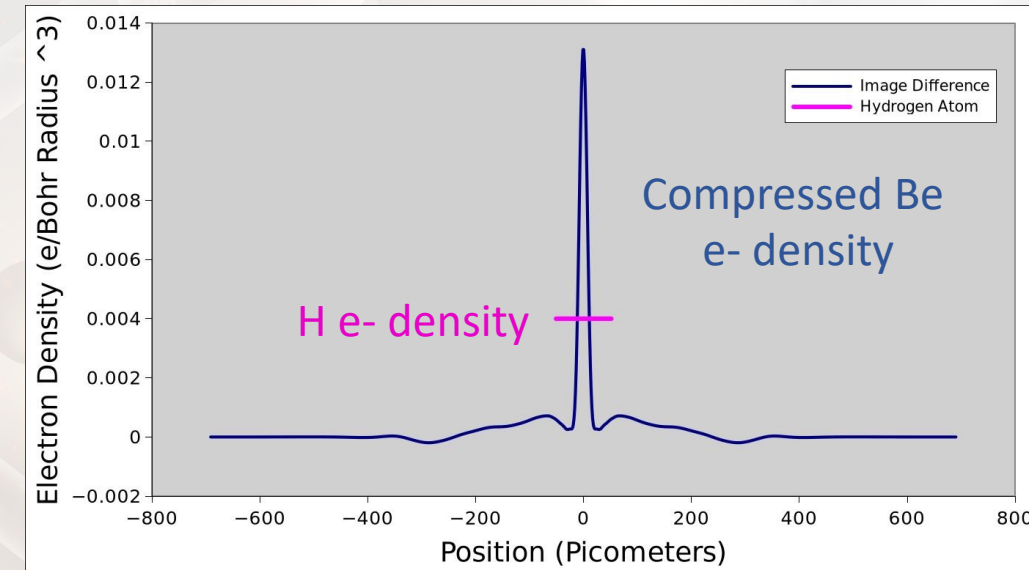
.1% compression gives

- 10x higher electron density in ⁷Be₄ nucleus
It Decays by Electron Capture

- Consistent with observed .8% reduction in *half life!*

*Electron wavefunction influences nuclear reactions!
So does electron screening.*

*Electrons are necessary for fusion²
and enhance Nuclear Reactions*



Broad electron density after subtractions

¹. L.P. Forsley and L.F. DeChiaro, "Electron Screened and Enhanced Nuclear Reactions", ICCF-24, (Menlo Park, CA) July 2020

². V. Pines, *et al.*, "Nuclear Fusion Reactions in Deuterated Metals", *Physical Review C*, **101** (2020) p. 044609

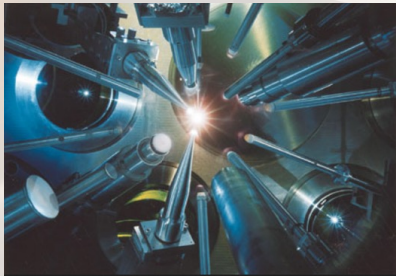
Fusion Comparisons and LENR PdD¹ Lattice Density

Fusion Types and “fuel” densities

Confinement Types Ion/electron density

Inertial $10^{26}/\text{cm}^3$

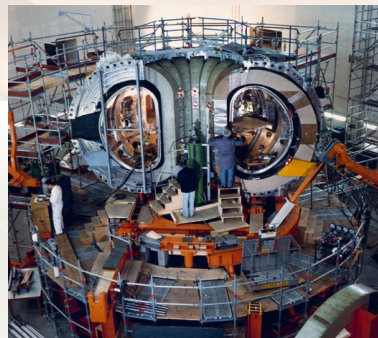
100 μm core



Omega (ICF)¹

Magnetic $10^{14}/\text{cm}^3$

7 m



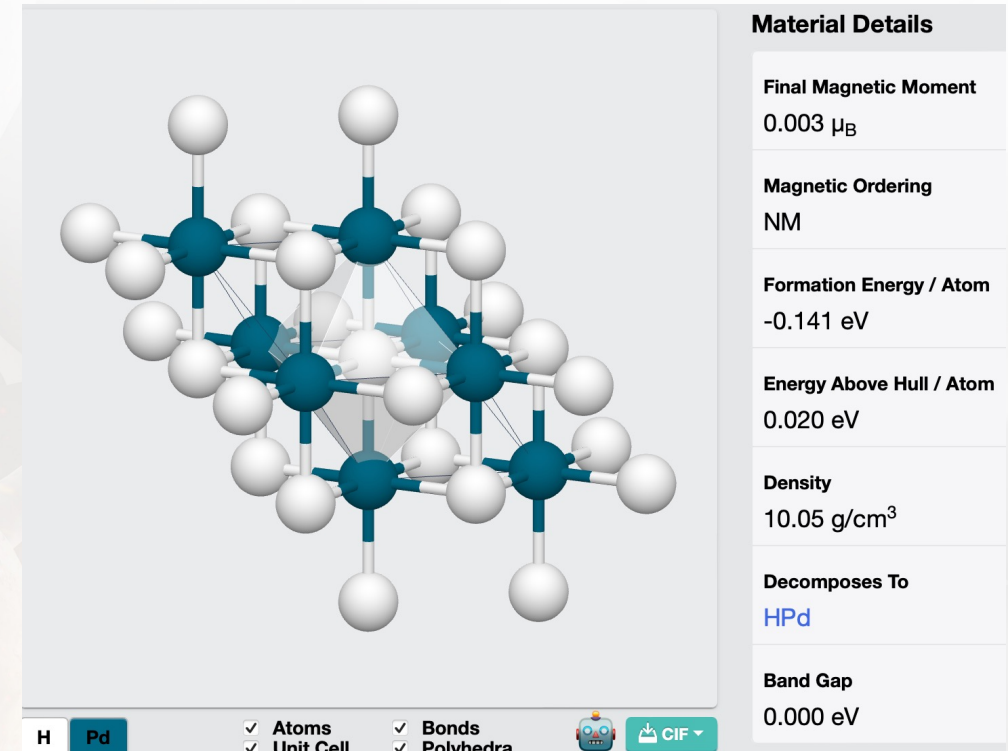
ASDEX (MCF)²

Solid State $10^{23}/\text{cm}^3$

2.54 cm



Co-dep
(Solid State/LCF)



Solid State PdD Lattice³

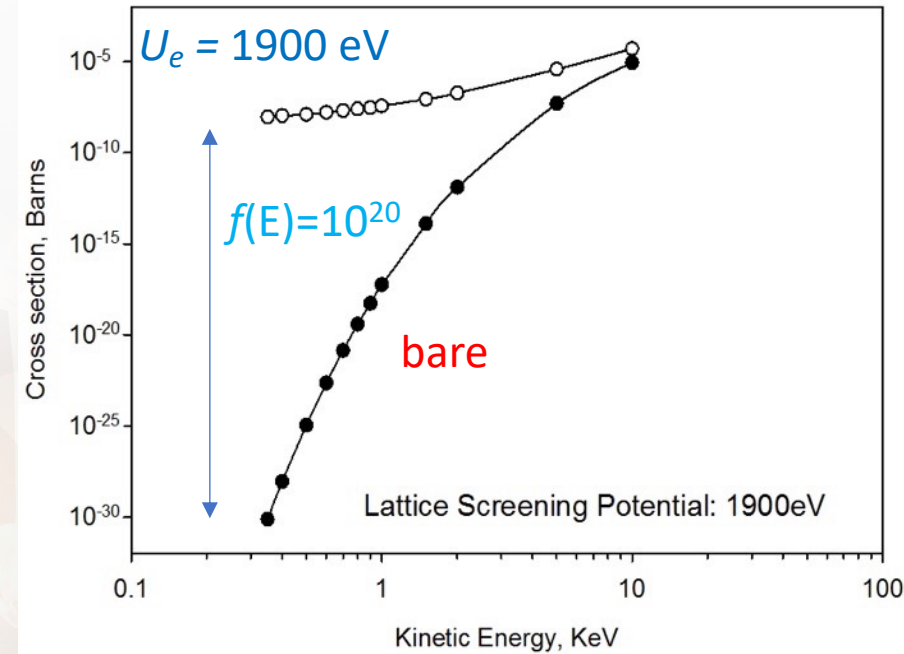
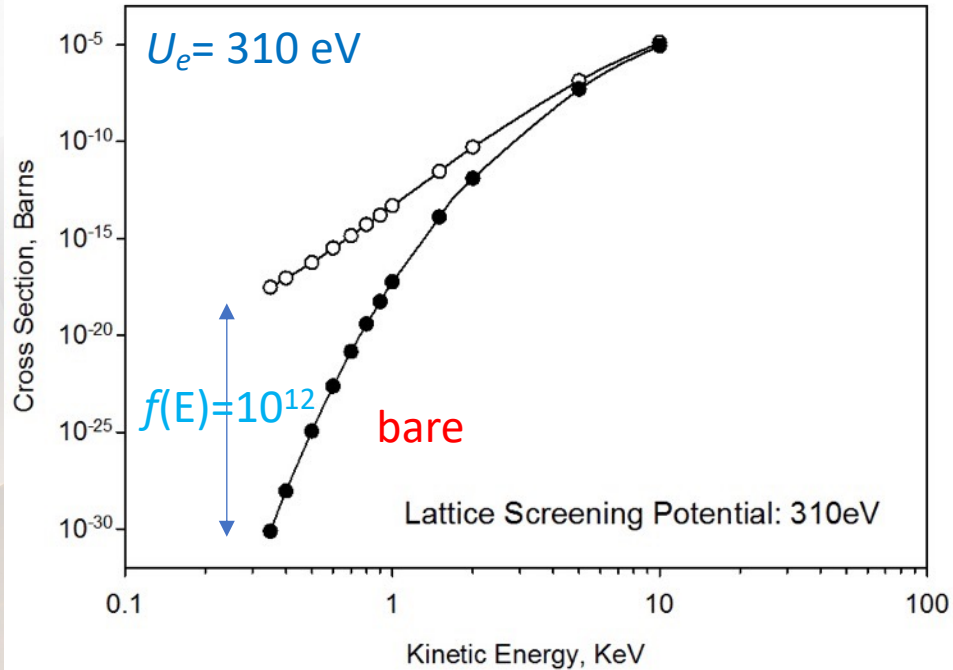
***A solid-state lattice has a billion times
higher fuel density than a tokamak!***

1. www.rochester.edu/currents/V29/V29N05/photos/Omega2.jpg

2. www.ipp.mpg.de/4047930/04_16

3. <https://legacy.materialsproject.org/materials/mp-24289/>

Pd Lattice U_e Measured^{1,2} and Calculated^{2,3}



Bare cross-section

Enhancement factor

Enhanced Experimental cross-section

$$\sigma_{bare}(E) = S(E) \cdot E^{-1} \cdot \exp(-G(E))$$

$$f(E) = \frac{E}{(E + U_e)} \cdot \exp\{G(E) - G(E + U_e)\}$$

$$\sigma_{exp}(E) = \sigma_{bare}(E) \cdot f(E)$$

E Kinetic Energy, keV

U_e Electron Screening, keV

$G(E)$ Gamow Factor

$S(E)$ Astrophysical Factor

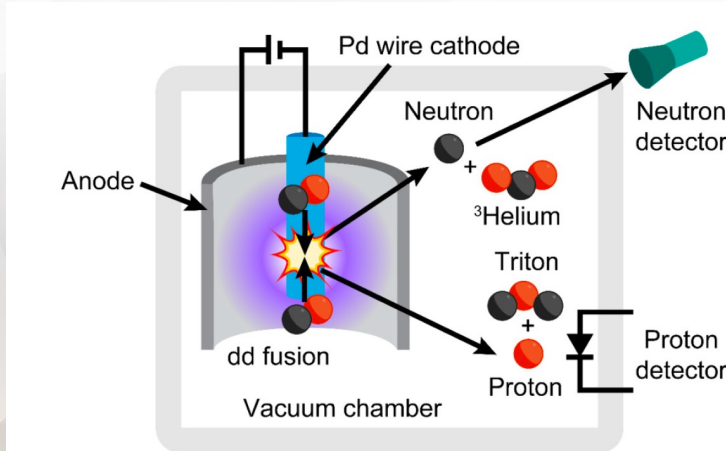
Screening works below 10 keV Kinetic Energy and increases nuclear reaction rates by potentially 20 orders of magnitude.

¹J. Kasagi, H. Yuki, T. Baba and T. Noda, "Low Energy Nuclear Fusion Reactions in Solids", 8th International Conference on Cold Fusion. Italy: Italian Physical Society, Bologna, Italy. Lerici (La Spezia), (2000) Figure 4.

²M. Lipoglavšek and U. Mikac, "Electron Screening in Metals", *AIP Conf. Proc.* **1377**, (2011) 383

³Calculated screening U_e and enhancement factor $f(e)$ by V. Pines and M. Pines, NASA Advanced Energy Conversion Project

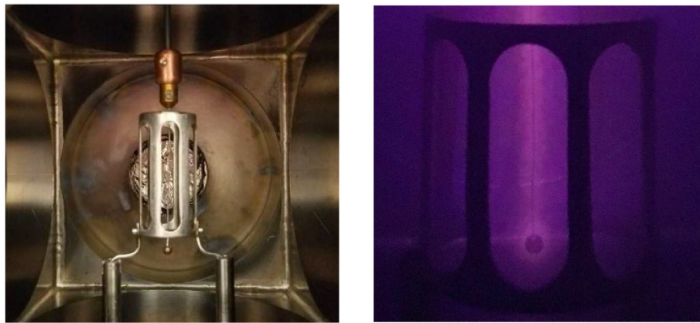
Electron Screened Pd/D loaded by Glow Discharge^{1,2} with D(d,n)³He Fusion Neutrons



D-D fusion neutrons observed with Eljen-309 scintillator-based neutron detectors.

*Neutron yield is a function of Pd cathode voltage
Fusion rate 100 times higher rate than for bare nuclei
due to Gamow Factor enhancement $f(E)$*

*electron screening potential, $U_e = 1000 \pm 250$ eV
with $D^+ < 2$ keV (center of mass frame)*



LBNL Glow Discharge

1.25 keV – 6 keV, center-of-mass

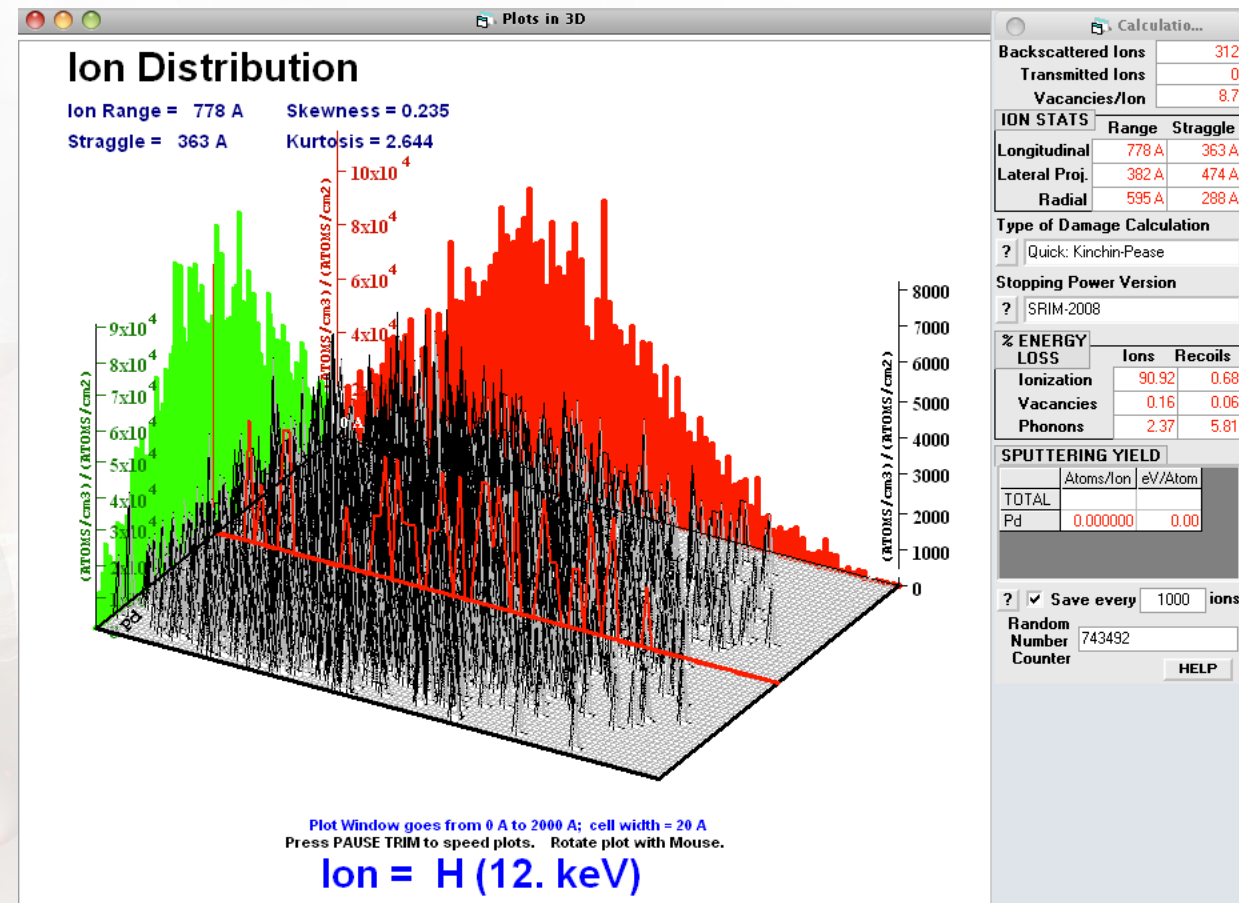
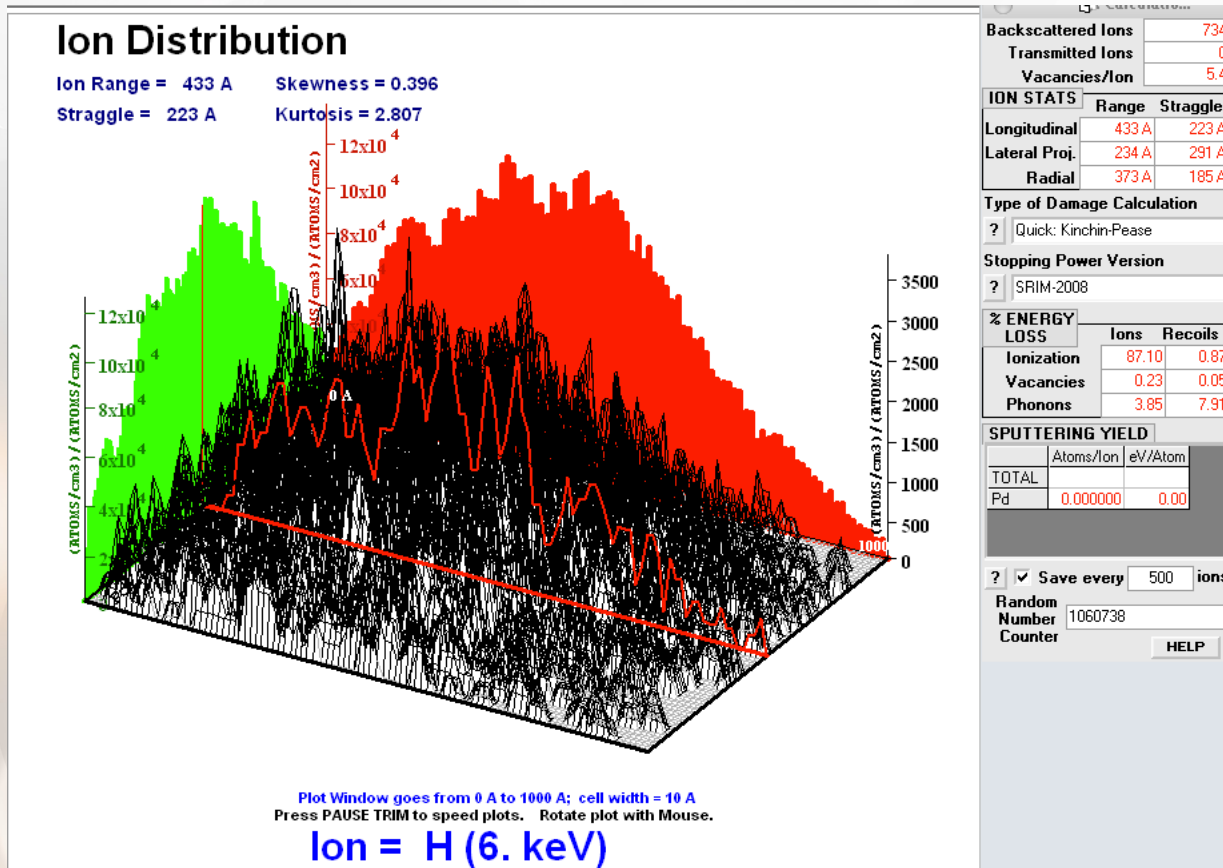
Figures reproduced from Schenkel² with the permission of AIP Publishing.

¹. C. P. Berlinguette, et al., “Revisiting the cold case of cold fusion”, *Nature*, **570** (2019)

². T. Schenkel, et al., “Investigation of light ion fusion reactions with plasma discharges”, *J. Appl. Phys.* **126**, 203302 (2019)

<https://aip.scitation.org/doi/abs/10.1063/1.5109445>

Modeling¹ Deuterons in PdD



433 Angstrom Range

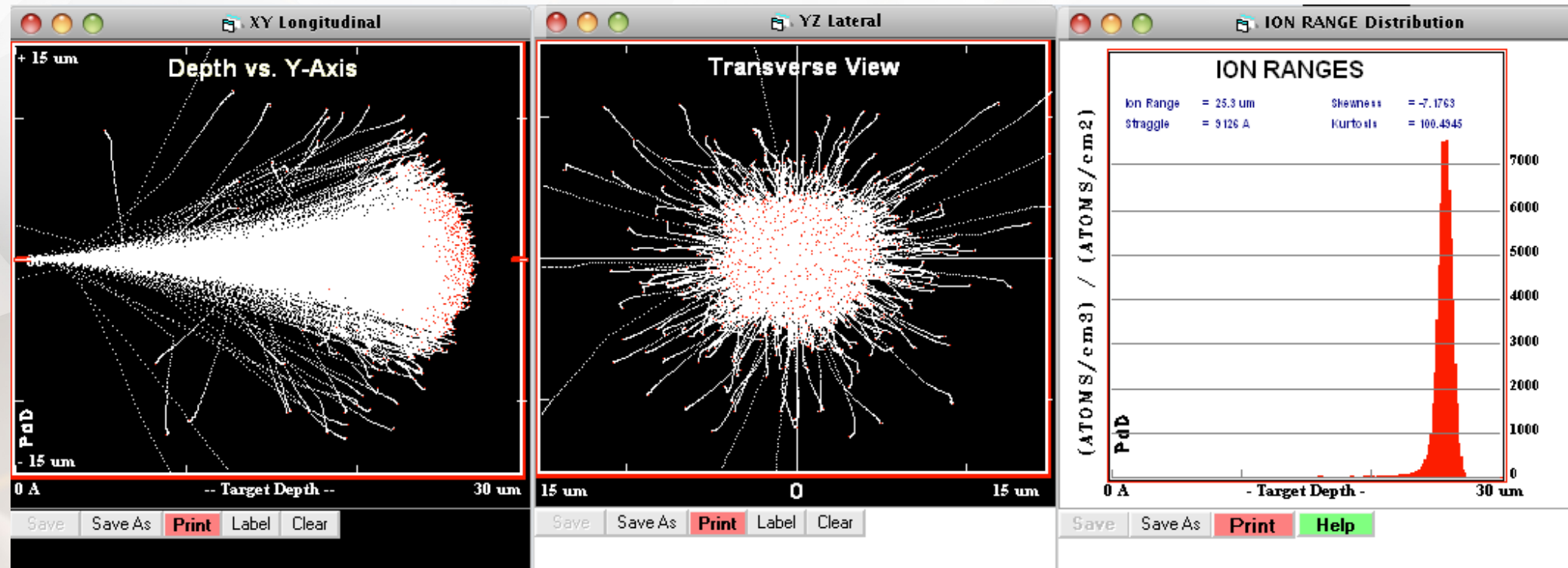
778 Angstrom Range

SRIM/TRIM models of some of Schenkel's plasma discharge deuterons

Nuclear elastic momentum transfer but not nuclear reactions!

Bragg Peak

3 MeV D(d,p)T Proton in PdD



Bragg Peak¹ for the 3 MeV proton is at 25.3 μm

D(d,p)T 3 MeV screened proton can scatter off another deuteron, transfer momentum and heat it. This induces other other reactions.

Where are the Pd fluorescence x-rays? Low probability of inducing them!²

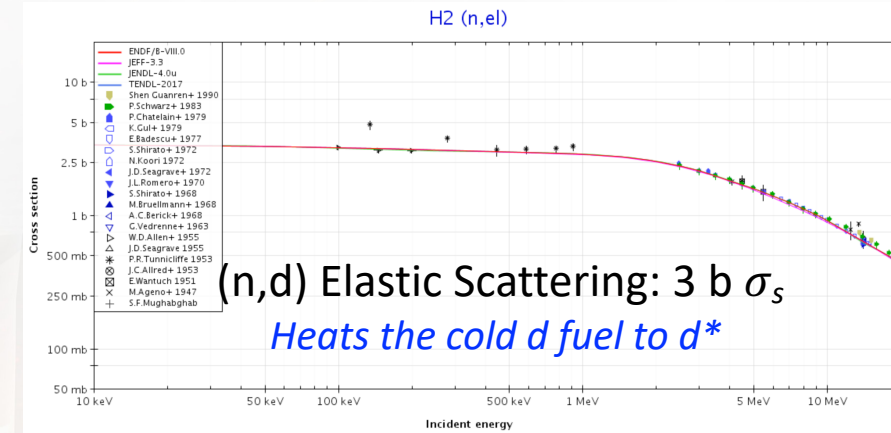
¹ J. F. Ziegler, M.D. Ziegler, J.P. Biersack, "SRIM - The stopping and range of ions in matter", *Nuclear Instruments and Methods in Physics Research Sec. B*, **268** (11-12) (2010) pp. 1818-1823.

² L.P.G. Forsley, P.A. Mosier-Boss, P.K. McDaniel and F.E. Gordon, "Charged Particle Detection in the Pd/D System: CR-39 SSNTD vs. Real-Time Measurement of Charged Particle Stimulated Pd K Shell X-rays", *Electrochimica Acta* **88** (2013) pp 373-383.

Neutron or Screened Ion Heating of Lattice Deuterons

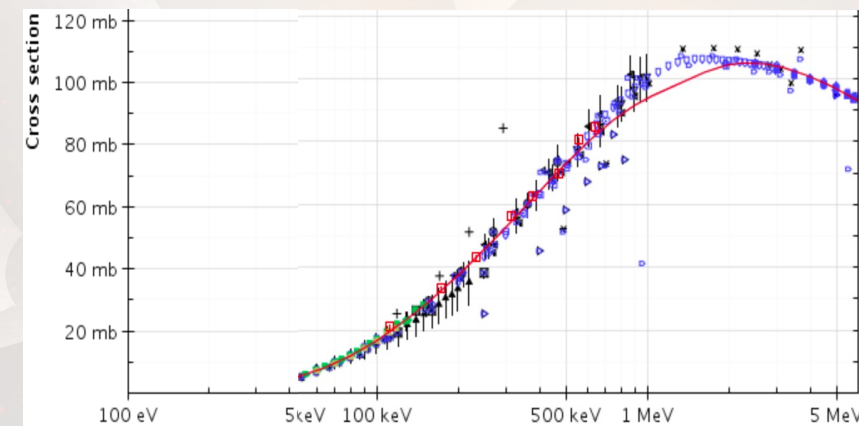
- The lattice material and density determine neutron and screened ion:
 - Mean-free path and scattering cross-section:
 - SRIM/TRIM for Ion scattering
 - JANIS Tables for neutrons
 - Nuclear Capture cross-sections
 - Janis Tables for ions and Neutrons
- *Scattering heats “cold” deuterons resulting in boosted reactions*
- *MCNP and GEANT-4 can't model the nuclear reactions of ions < 1 MeV! No Gain!*

Neutron scattering Cross-section



JANIS tables

DD fusions Cross-section



JANIS tables

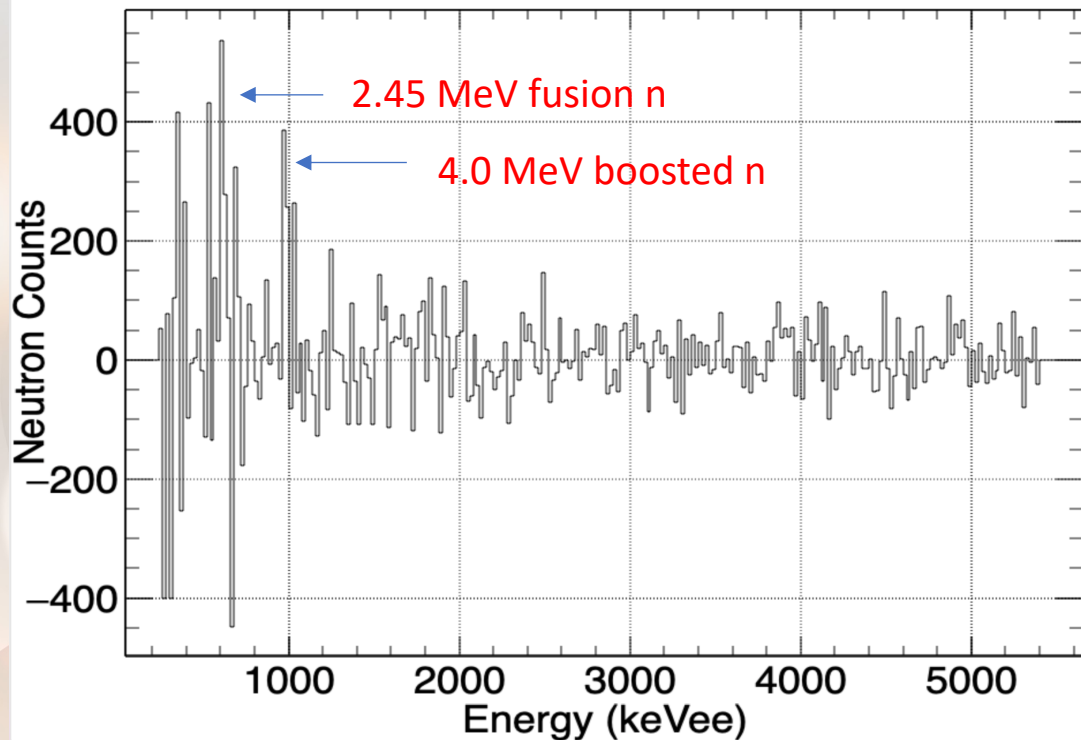
Electron screening increases probability!

Boosted Nuclear Reactions in PdD and TiD₂

Two different triggers and two different lattices, similar reactions!

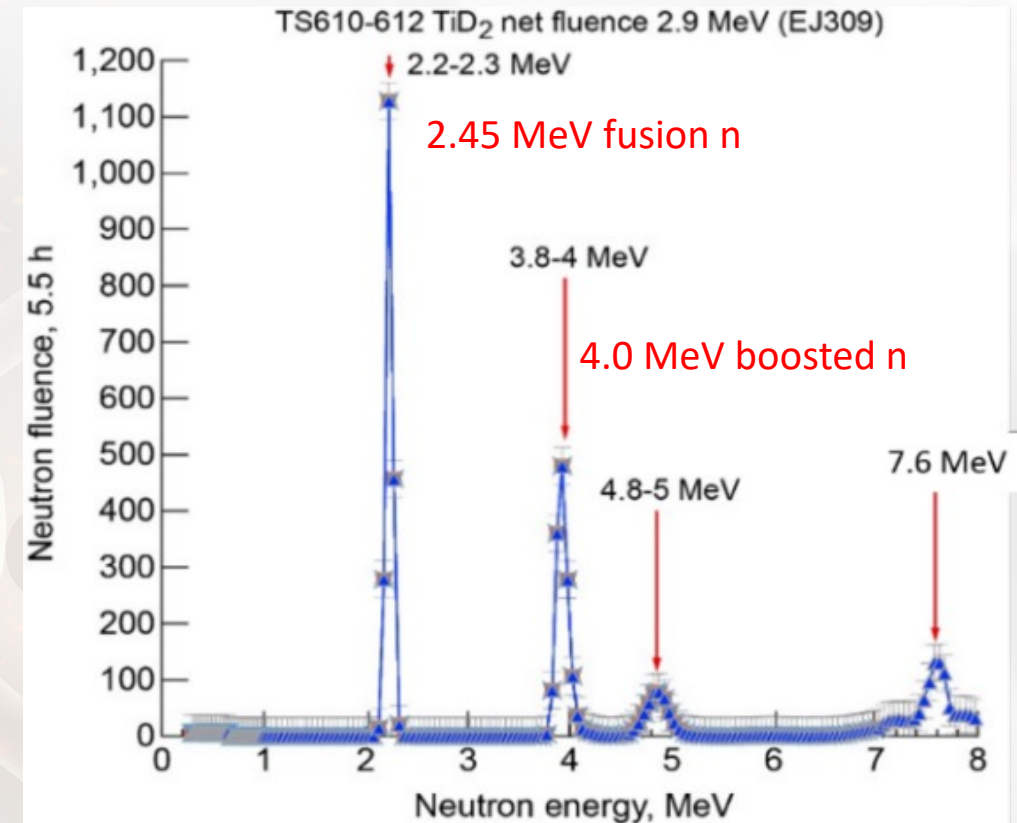
< 10 V electrolysis

Exp Net Minus No Current Net (Time Normalized)



$D(d,n)^3\text{He}$
 $D(d,pT$
Boosted
 $D(d^*,n)^3\text{He?}$

2.9 MV electron beam bremsstrahlung



¹Electrolytically-initiated Fusion in PdD, (CIF RUN 5)

²Bremstrahlung-initiated Fusion in TiD₂

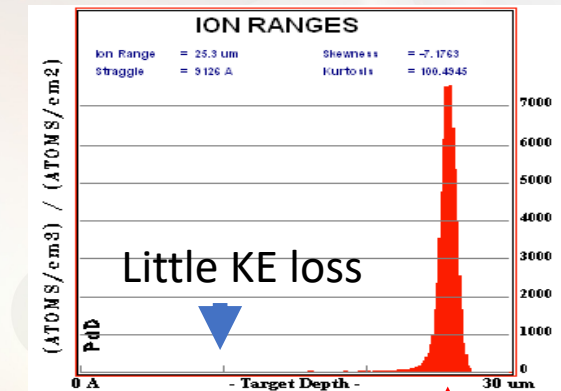
¹ US Patent 8,419,919, "System and Method to Generate Particles" (2013)

² B.M. Steinetz, et al., "Novel Nuclear Reactions Observed in Bremsstrahlung-Irradiated Deuterated Metals", Phys Rev C, 101, (2020) 044610.

Conclusion



- **Screening Near Bragg Peak Should Enhance Solid State Fusion Reactions**
 - **Consequences:** *important to diagnostics!*
 - Fast fusion protons barely slowed traversing the lattice < 25 μm
 - 3 MeV protons > 25 μm from the surface, won't reach the surface and be detected
 - **Conundrums**
 - Few fast neutrons seen in most solid state fusion (save co-dep and bremsstrahlung LCF)
 - *No neutron heating!*
 - Ion electron screening maximum at the the Bragg Peak, *but have ions have no kinetic energy!*
 - **Solution**
 - Fusion proton > 3 MeV KE has a few keV just before the Bragg Peak
 - The screened, effective deuteron kinetic energy > 1 keV (Fermi-degeneracy, conduction band)
 - *Effective plus real kinetic energy is > 3 keV, or 33 million degrees C.*
 - Add 1 keV from strained Pd deuteron adds 1 keV kinetic energy¹
 - Effective, strained, plus kinetic energy is > 4 keV, or 44 million degrees C.



Bragg Peak

Solid State Hot Fusion in a shielded lattice is inevitable!

References



- E.E. Salpeter, “Electrons Screening and Thermonuclear Reactions”, *Australian J. Physics*, **7**, (1954) p. 373.
- K. Hagino and A.B. Balantekin, “Radiation correction to astrophysical fusion reactions and the electron screening problem”, *Physical Review C*, **66**, (2002) p. 055801.
- H. J. Assenbaum, K. Langanke, and C. Rolfs, “Effects of Electron Screening on Low-Energy Fusion Cross Sections” *Z. Phys. A*, **327**, (1987) pp. 461–468.
- K. Czerski, *et al.* “Experimental and Theoretical Screening Energies for the $2\text{H(d,p)}3\text{H}$ Reaction in Metallic Environments”, *Eur. Phys. J. A*, **27**, (2006) pp. 83–88.
- L.P.G. Forsley, P.A. Mosier-Boss, P.K. McDaniel and F.E. Gordon, “Charged Particle Detection in the Pd/D System: CR-39 SSNTD vs. Real-Time Measurement of Charged Particle Stimulated Pd K Shell X-rays”, *Electrochimica Acta* **88** (2013) pp 373-383.
- L.P. Forsley and L.F. DeChiaro, “Electron Screened and Enhanced Nuclear Reactions”, ICCF-24, (Menlo Park, CA) July 2020
- <https://legacy.materialsproject.org/materials/mp-24289/>
- <https://www.bnl.gov/nsrl/userguide/bragg-curves-and-peaks.php>
- <https://www.nuclear-power.com/nuclear-power/reactor-physics/interaction-radiation-matter/interaction-heavy-charged-particles/stopping-power-bethe-formula/>
- J. Kasagi, H. Yuki, T. Baba and T. Noda, “Low Energy Nuclear Fusion Reactions in Solids”, *8th International Conference on Cold Fusion*. Italy: Italian Physical Society, Bologna, Italy. Lerici (La Spezia), (2000) Figure 4.
- M. Lipoglavšek and U. Mikac, “Electron Screening in Metals”, *AIP Conf. Proc.* **1377**, (2011) 383
- V. Pines, *et al.*, “Nuclear Fusion Reactions in Deuterated Metals”, *Physical Review C*, **101** (2020) p. 044609
- T. Schenkel, *et al.*, “Investigation of light ion fusion reactions with plasma discharges”, *J. Applied Physics*, **126**, (2019) p. 203302.
- B.M. Steinetz, *et al.*, “Novel Nuclear Reactions Observed in Bremsstrahlung-Irradiated Deuterated Metals”, *Phys Rev C*, **101**, (2020) 044610.
- US Patent 8,419,919, “System and Method to Generate Particles” (2013)
- J. F. Ziegler, M.D. Ziegler, J.P. Biersack, “SRIM - The stopping and range of ions in matter”, *Nuclear Instruments and Methods in Physics Research Sec. B*, **268** (11-12) (2010) pp. 1818-1823.

Acknowledgements



- Support provided by the NASA Advanced Energy Conversion and Lattice Confinement Fusion Projects under the Planetary Science Division, Planetary Exploratory Science Technology Office (PESTO) and the NASA Innovative Advanced Concepts Program, using Lattice Confinement Fusion Fast Fission to visit Icy Worlds.
- Global Energy Corporation and the US-Asia Institute supported Trackers STEM Program™ with the Anthropocene Institute.
- Ms. Victoria Leist's assistance in analyzing Solid State Nuclear Track Detectors.
- Dr. Bayar Baramsai for Pulse Shape Discrimination and Neutron Unfolding codes.



Studley

In memory of Dr. Marianna Pines

(No dog was hurt in research for this presentation, only bored.)