Advanced Energy Conversion (AEC) Project

Lattice Confined Fusion (LCF) Workshop

Dr. Theresa Benyo*, Mr. Len Dudzinski^,
Dr. Bruce Steinetz*, Dr. Arnon Chait*, Dr. Vladimir Pines#
Mr. Lawrence Forsley**

May 21, 2020

*NASA Glenn Research Center
#PineSci Consulting
^NASA Headquarters
**Global Energy Corporation

LCF Workshop: Introduction

Mr. Len Dudzinski
Chief Technologist, Planetary Science Division
NASA HQ



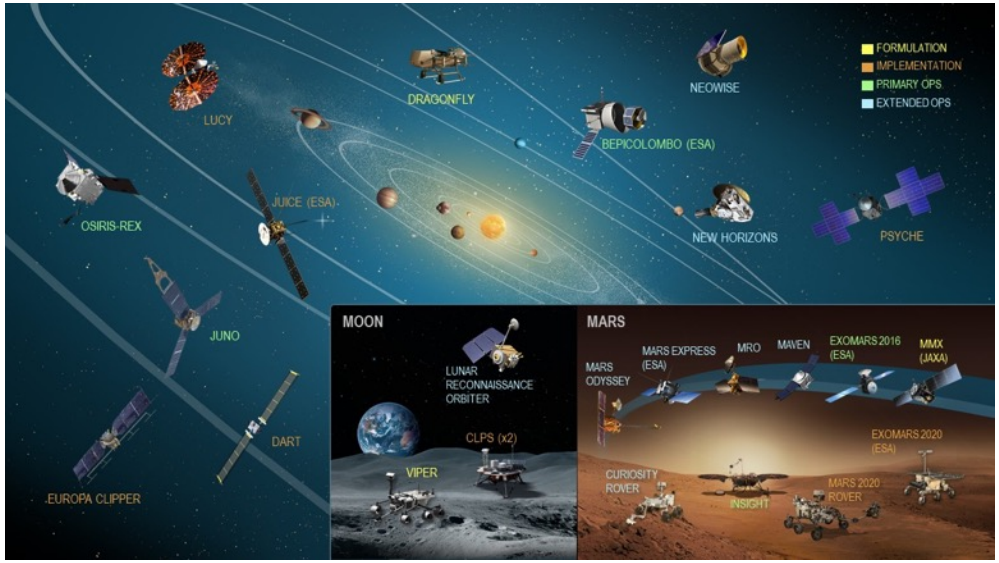
NASA Glenn Research Center

Advanced Energy Conversion Team

May 21, 2020

Introduction

- Discovery of the phenomena
- Planetary Science interest
- Workshop Objectives



LCF Workshop Objectives

- Objective 1
  - NASA Glenn Research Center (GRC) will disseminate the key findings in our recently published *Phys Rev C* journal papers detailing experiments and theory to our NASA HQ Sponsor, a NASA panel, and select invited external researchers.
  - The presentations will emphasize electron screening in a confined lattice which allows enhanced nuclear fusion.
- Objective 2
  - Invite feedback from invited panelists and questions from participants regarding the work presented.

LCF Workshop: Agenda

Dr. Theresa Benyo
Analytical Physicist, Materials & Structures Division
NASA GRC



NASA Glenn Research Center

Advanced Energy Conversion Team

May 21, 2020

Welcome

- AEC Team will highlight and discuss:
  - "Novel Nuclear Reactions Observed in Bremsstrahlung-irradiated Deuterated Metals"
  - "Nuclear Fusion Reactions in Deuterated Metals"
- Opportunity for questions
  - Use special I/O tool to send questions to the team
  - I/O tool will be open at certain times throughout the workshop
  - In order to keep on schedule, any questions not asked will be saved and addressed after the workshop

https://arc.cnf.io/sessions/z7mg/#!/dashboard

Welcome

- Panel Session
  - Invited scientists will be presenting their feedback on the 2 journal papers
  - Participants will be able to ask questions of the panel
- Breaks
  - Time allotted for breaks will be followed strictly to keep us on schedule

Virtual LCF Workshop Agenda: Intro

- Executive Summary of Significant Findings: B. Steinetz & A. Chait
  - Background/Introduction
  - LCF animation
  - Key Accomplishments
  - Phys Rev C Journal Papers
    - "Novel Nuclear Reactions Observed in Bremsstrahlung-irradiated Deuterated Materials" (Experiment)
    - "Nuclear Fusion Reactions in Deuterated Metals" (Theory)
  - Why Significant?

Virtual LCF Workshop Agenda: Experiments

- Presentation of Experimental Paper: B. Steinetz
  - Background/Intro
  - Experiment Procedure + Measurements
    - Dynamitron and Specimen Descriptions
    - Experiment Flow chart
    - Neutron Spectroscopy
    - Detection Efficiency
  - Key Results & Discussion
    - Evidence of Fusion neutrons
    - Other Enhanced Nuclear reactions
    - Comparison of measured and theoretical calculations
    - Comparison of findings to published fusion studies
  - Summary: Key findings
  - Question/Answer

Virtual LCF Workshop Agenda: Theory

- Break
- Presentation of Theory Paper: V. Pines & A. Chait
  - Introduction
  - Main Elements of Theory Paper
    - Nuclear Fusion with Electron Screening: (shell, conduction, plasma electrons)
    - Small vs. Large Angle Coulomb Scattering and Probability of Fusion
      - Influence of Electron Screening
    - Scattering of Charged and Uncharged Particles off a Deuteron
      - Elastic cross section
      - Energy transfer
  - Conclusions and Significance
- Question/Answer

Virtual LCF Workshop Agenda: Panel Session & Wrap-up

- Introduce Panel Session: T. Benyo
  - Key Discussion Topics for Panelists
    - Comments on experiments
    - Comments on theory
  - Introduce Panelists
- LCF Panel Session
  - Thoughts/Feedback
    - Dr. Matt Forsbacka (NASA HQ)
    - Dr. Ron Litchford (NASA HQ)
    - Dr. Michael Houts (NASA MSFC)
    - Mr. John Scott (NASA JSC)
  - Question/Answer
- Going Forward: L. Forsley
- Wrap-up and Summary: T. Benyo

LCF Workshop: Executive Summary

Dr. Bruce Steinetz and Dr. Arnon Chait
Senior Technologist and Senior Scientist
NASA GRC



NASA Glenn Research Center

Advanced Energy Conversion Team

May 21, 2020



AEC Project Charter

- Overall Goal
  - Power/energy sources for long-duration deep space mission
- Basic Research Objectives
  - No solar energy
  - Non-radioactive starting materials
  - No actinide fission/decay-based solution
  - Benign operations
    - >10 yr lifetime
  - Power < kW level
  - Space rated systems: weight/Watt

NO CONVENTIONAL ENERGY SOURCE EXISTS TODAY TO MATCH THESE REQUIREMENTS

Team Members

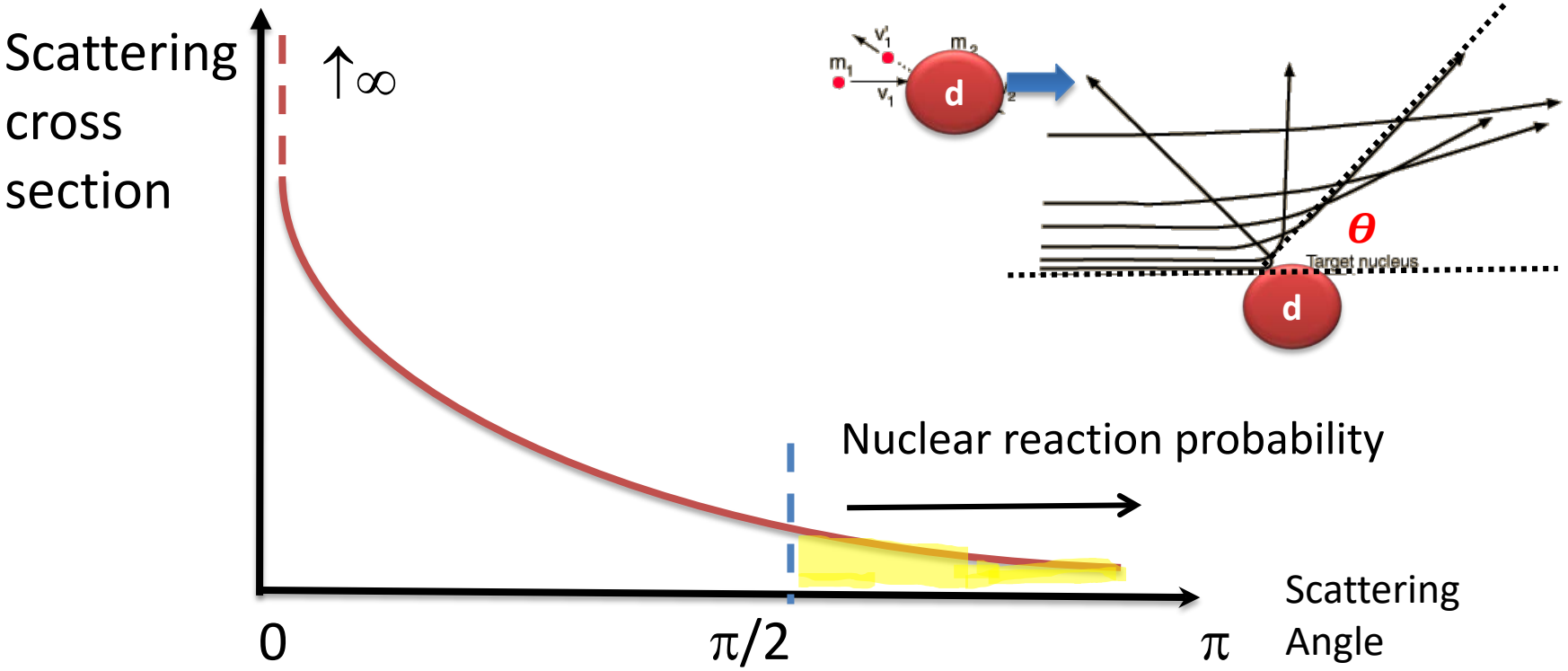
Member	Role
Bruce Steinetz	Principal Investigator (PI)
Rich Martin	Deputy Principal Investigator
Arnon Chait	Senior Science Lead
Vladimir Pines	Senior Theoretical Physicist
Marianna Pines	Scientist
Theresa Benyo	Analytical/Theoretical Physicist (*Transitioning to PI)
Larry Forsley	Senior Lead Experimental Physicist
Carl Sandifer II	Project Manager
Bayar Baramsai/Phil Ugorowski	Senior Experimental Physicists: Data Acquisition
Mike Becks/Tracy Kamm	Test and Sample Coordinators
Nicholas Penney	Test Equipment Engineer
Robert Hendricks/Gus Fralick	Senior Scientist / Senior Physicist
Chris Blasio	Radiation Safety Officer
Rick Galloway	IBA Test Engineer/Dynamitron Lead
Jim Scheid	IBA Dynamitron Technician
Fred Van Keuls/Wayne Jennings /Frank Lynch	Materials Loading
Laura Becker/Lorie Passe	Editor / Manuscript Lead

Brief Background/Timeline of Current Work

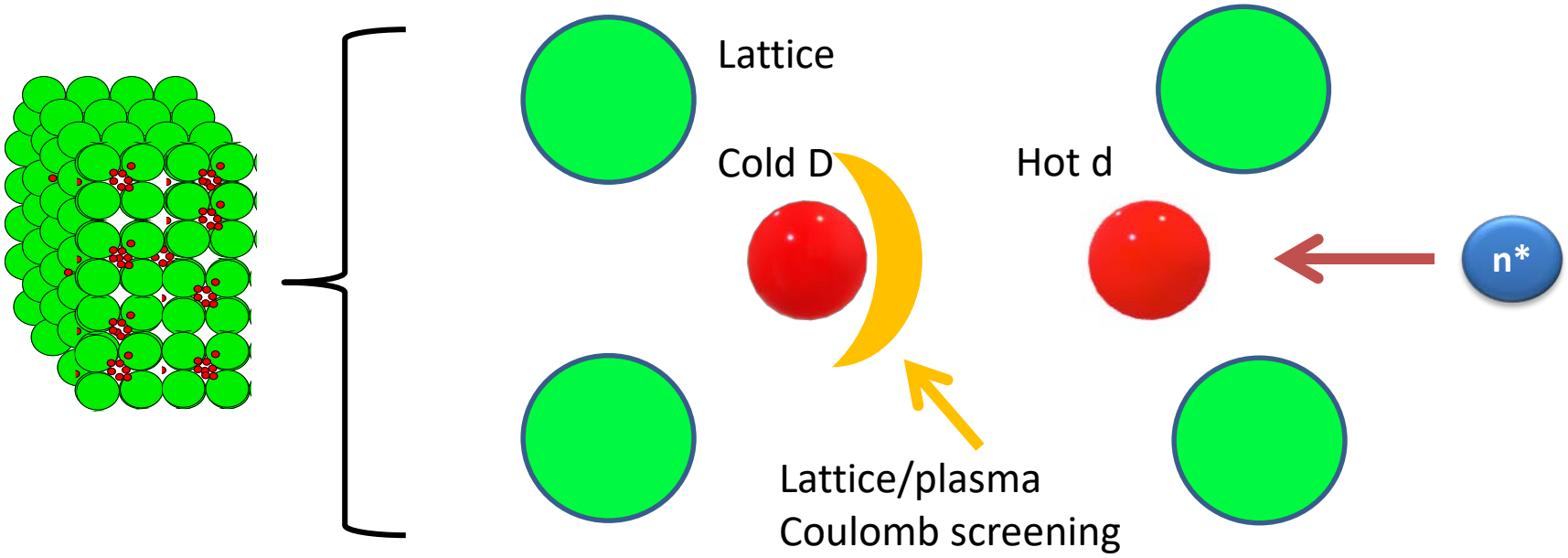
Date	Activity
2012-2016	AEC Project early years: investigated novel reactions observed in highly deuterated materials using various initiation schemes
Feb. 2017	HQ Science Panel Review of AEC: Commissioned Bremsstrahlung Radiation Test Campaign
Sept 2018	Briefed Findings to HQ Sponsor (Science Mission Directorate)
Oct 2018	Submitted two Articles to Phys Rev C Journal for consideration
2019 (various)	Interactions with Journal Reviewers, Editors, Manuscripts
Dec 2019	Journal Papers Accepted for Publication
March 2020	Journal Papers Published On-line; April Issue of Phys Rev C
May 2020	Lattice Confined Fusion Workshop

Hot Fusion: A Brief Background

- Simple process: collide accelerated beams of deuterons to fuse
  - But in practice, most deuterons will be elastically scattered
- Why you can't practically fuse bare nuclei
  - Coulomb barrier scattering cross section at small angles is unbounded
  - Large angle scattering results in smaller distances between the deuterons, at which quantum tunneling becomes possible, increasing transparency of Coulomb barrier



Screened-Process Description



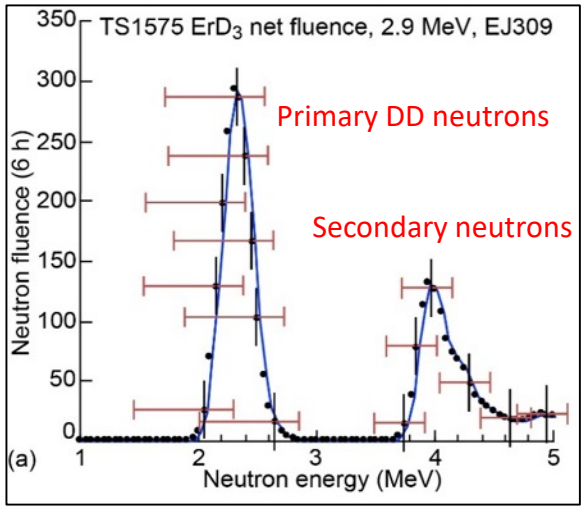
- Reactions are highly localized: majority of the fuel is cold
  - Only use energy to heat the projectile d, not the entire fuel D
- D-D interactions are highly screened: most favorable large/small angle scattering probability
- Lattice provided screening allows interaction with the parent atoms resulting in subsequent O-P reactions → further d* heating
- Process control is possible through:
  - Number and energy of neutron source: fusion process is not self-sustainable
  - Customizing fuel and lattice elements

Key Accomplishments

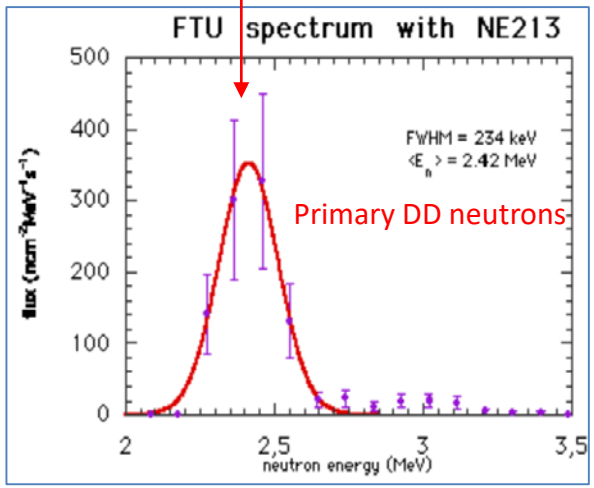
- Demonstrated d-D fusion in unique environment
  - Globally "cold" fuel – deuteron "heating" with photodissociation neutrons.
  - *Other neutron sources as trigger*
- Nuclear emissions measured by state-of-the-art calibrated neutron spectroscopy
- Observations correlated with model, external data, and supported by physics community
- Theory: astrophysics and accelerator experiments have provided insights in addressing Coulomb Barrier via lattice electron screening.
  - D-D interactions enhanced by favorable large/small angle scattering probability
  - High-Z interactions: O-P processes benefits from increased nuclear tunneling probability and further creates hot reaction products n*, p*
- Developed critical concentration of expertise in multiple disciplines, experimental and theoretical resources.

Demonstrated "hot" d-D fusion in "cold" fuel (deuterated metal) under bremsstrahlung radiation

Theoretical model predictive of observed reactions



DD Fusion 2.45 MeV neutron

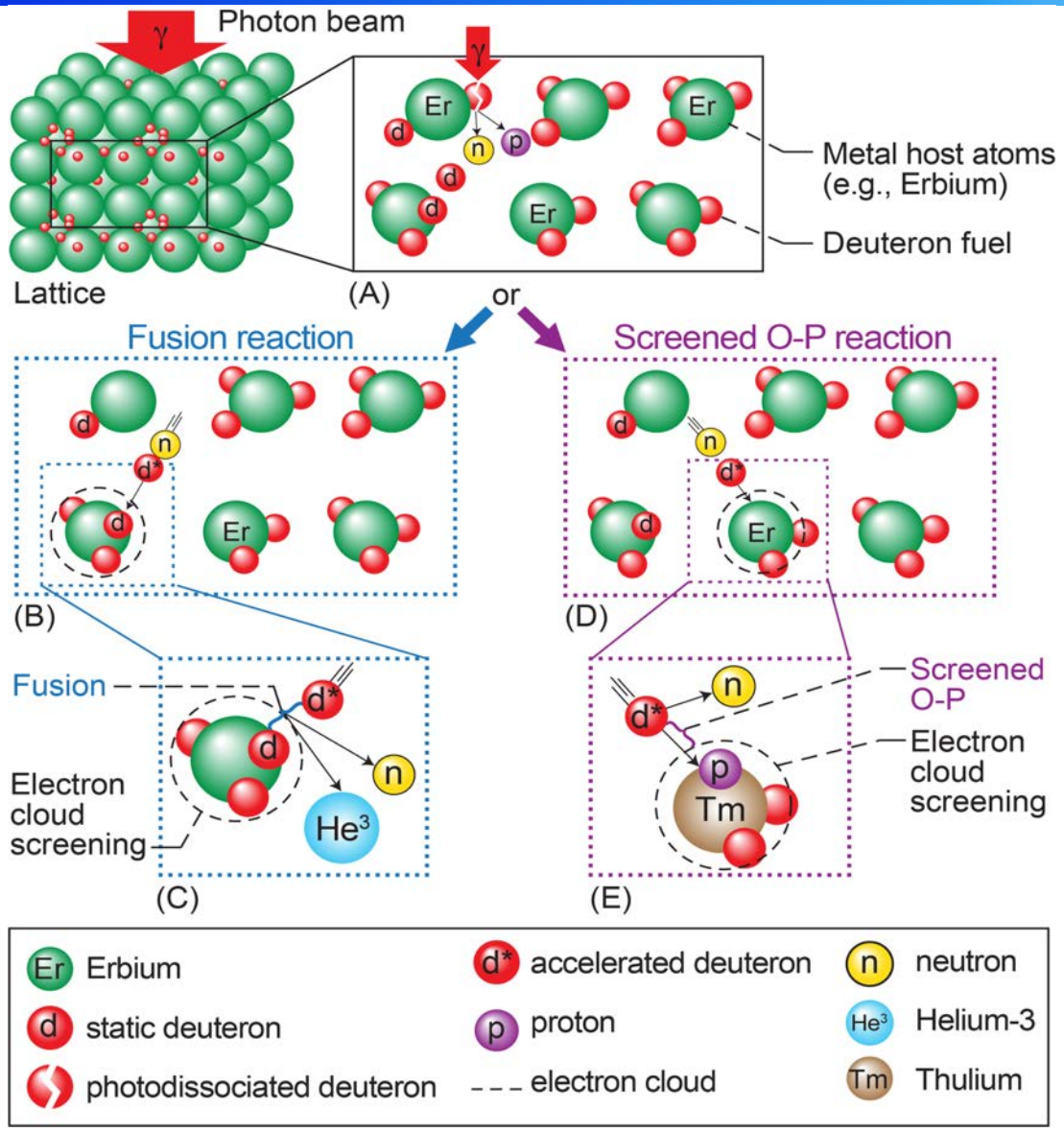


Italian ENEA Tokamak

Animation



Process Steps



Physical Review C Papers

Bremsstrahlung-induced Nuclear Reactions in Electron Screened, Deuterated Metal Lattices

Theoretical



APS physics

PHYSICAL REVIEW C

covering nuclear physics

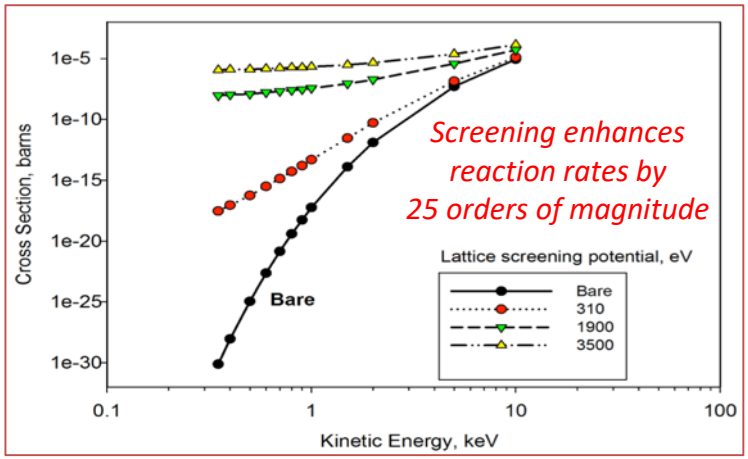
Accepted Paper

Nuclear fusion reactions in deuterated metals

Phys. Rev. C

Vladimir Pines, Marianna Pines, Arnon Chait, Bruce M. Steinetz, Lawrence Forsley, Robert C. Hendricks, Theresa L. Benyo, Gustave C. Fralick, Bayarbadrakh Baramsai, Philip B. Ugorowski, Michael D. Becks, Richard E. Martin, Nicholas Penney, and Carl E. Sandifer II

Accepted 10 December 2019



Electron Screened Enhanced Cross Sections

Experimental



APS physics

PHYSICAL REVIEW C

covering nuclear physics

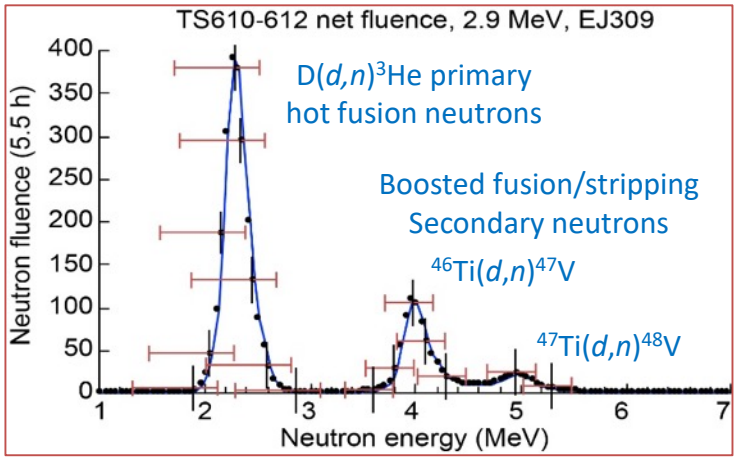
Accepted Paper

Novel nuclear reactions observed in bremsstrahlung-irradiated deuterated metals

Phys. Rev. C

Bruce M. Steinetz, Theresa L. Benyo, Arnon Chait, Robert C. Hendricks, Lawrence Forsley, Bayarbadrakh Baramsai, Philip B. Ugorowski, Michael D. Becks, Vladimir Pines, Marianna Pines, Richard E. Martin, Nicholas Penney, Gustave C. Fralick, and Carl E. Sandifer II

Accepted 6 December 2019



Fast Neutrons Observed

Lattice Confinement Fusion

Potential Technology Applications: With Successful Scaling of Process

- NASA
  - Solar power alternative for new classes of missions
  - Nuclear Enabled Propulsion for small satellites
  - Search for Lunar Water (neutron/gamma spectroscopy)
  - Neutron Spectroscopy in Jovian System (high radiation environment)
- Non-NASA
  - Manufacture of medical radioisotopes without HEU or LEU
  - Small scale terrestrial power plants

LCF Workshop: Experimental Paper

Dr. Bruce Steinetz
Senior Technologist and Principal Investigator
NASA GRC



"Novel nuclear reactions observed in bremsstrahlung-irradiated deuterated metals"

Bruce M. Steinetz, Theresa L. Benyo, Arnon Chait, Robert C. Hendricks, Lawrence P. Forsley, Bayarbadrakh Baramsai, Philip B. Ugorowski, Michael D. Becks, Vladimir Pines, Marianna Pines, Richard E. Martin, Nicholas Penney, Gustave C. Fralick, and Carl E. Sandifer, II

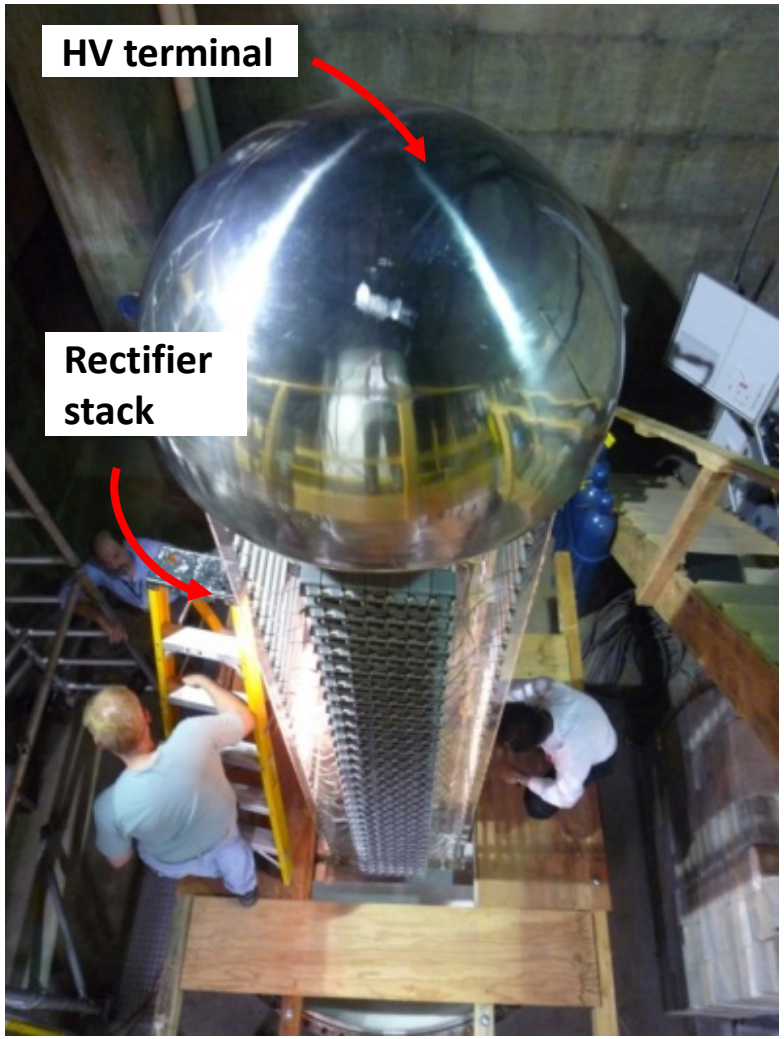
Phys. Rev. C 101, 044610 – Published 20 April 2020

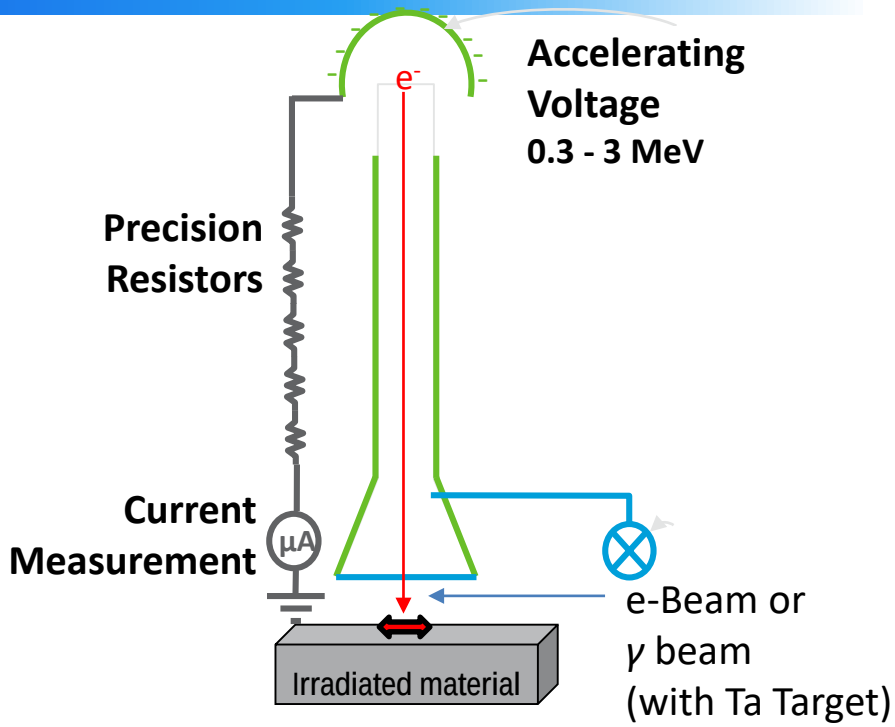
https://journals.aps.org/prc/abstract/10.1103/PhysRevC.101.044610

Introduction

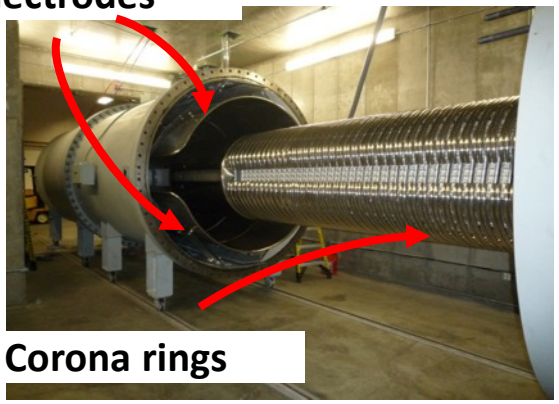
- Based on Science Panel direction for Bremsstrahlung irradiation campaign, AEC team examined several different beam providers
- Settled on IBA Industrial Dynamitron (Long Island NY)
- Dynamitron beam electron energy can be easily measured and controlled to ~1-2% of set point.
- Utilized IBA Dynamitron to:
  - Evaluate if specimen activation can be repeated with a well-calibrated beam
  - Utilize improved neutron diagnostics to measure/record activity during the test to allow better understanding of the physical mechanism(s) at work
- Question/Answer Tool Open
  - https://arc.cnf.io/sessions/z7mg/#!/dashboard

IBA Dynamitron
Simple Measure of Accelerating Voltage

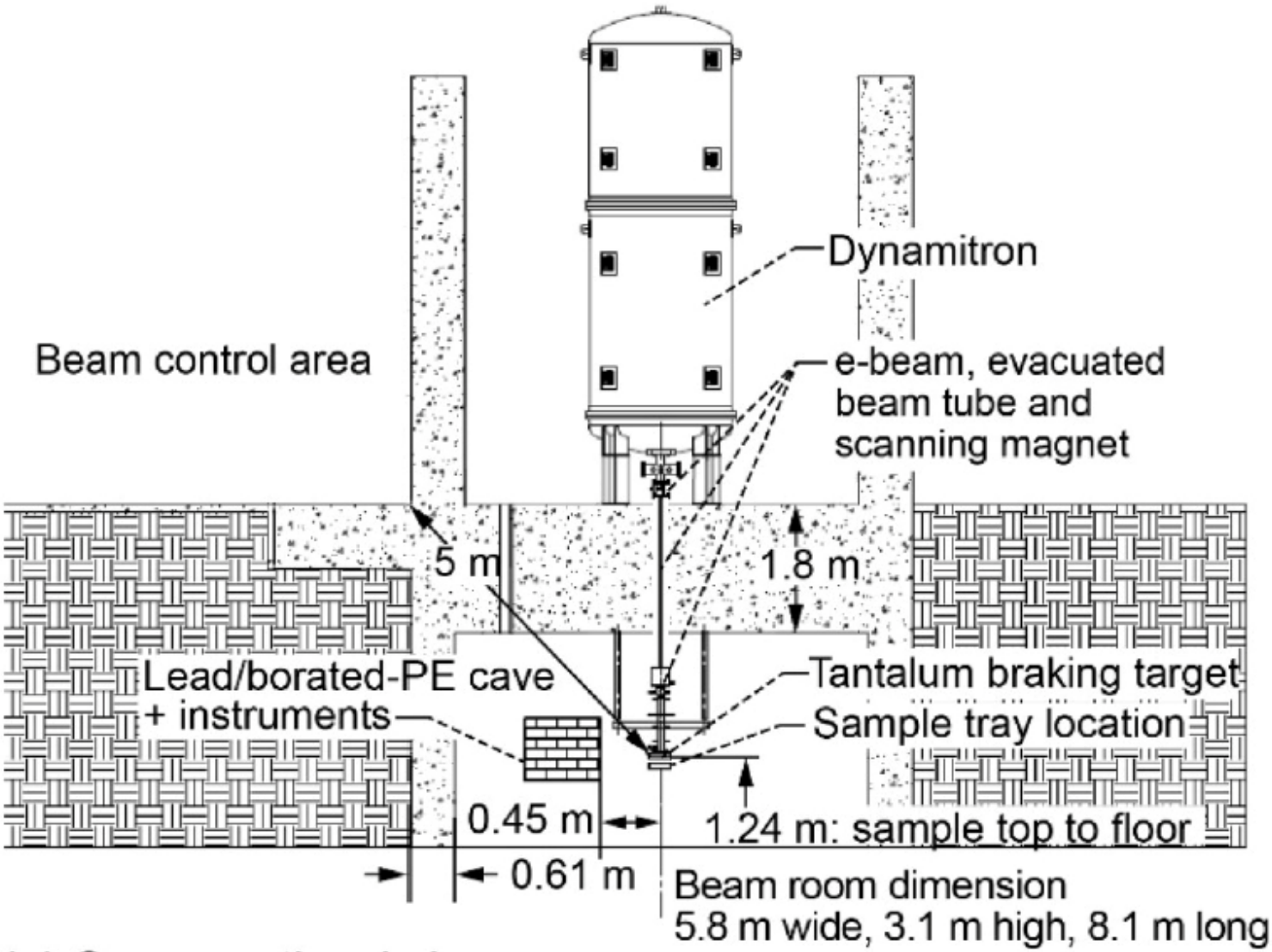




RF electrodes



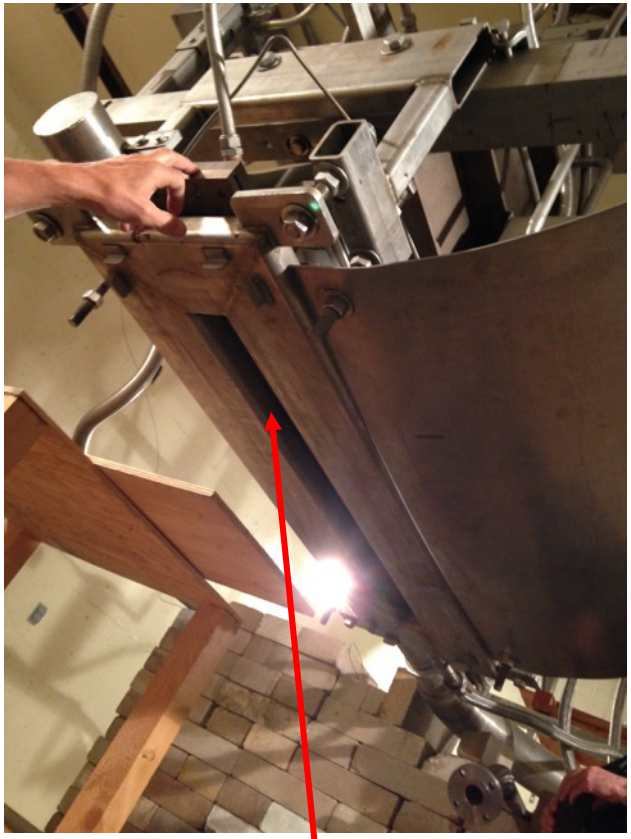
IBA Facility Diagram



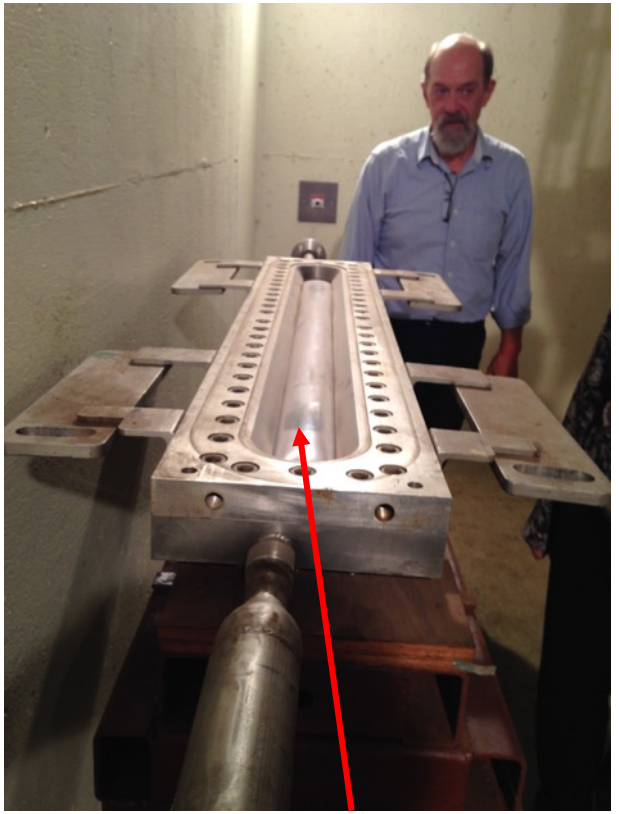
Beam Room Images
IBA (Long Island, NY)



Beam Test Station

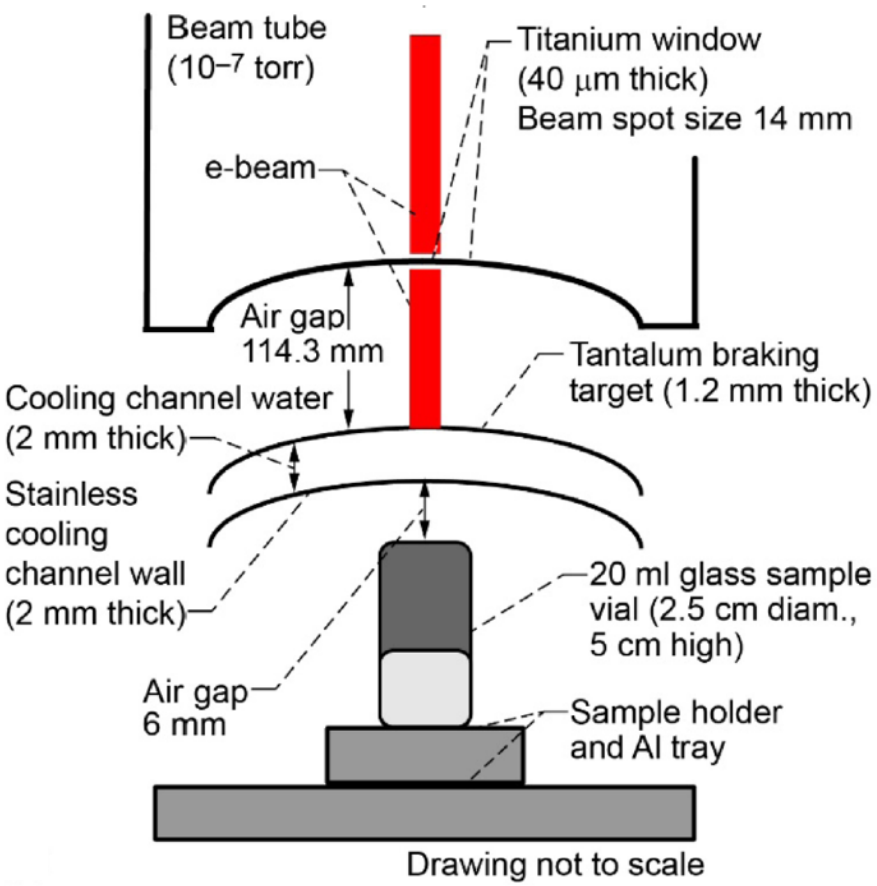


Electron Beam Exit Plane



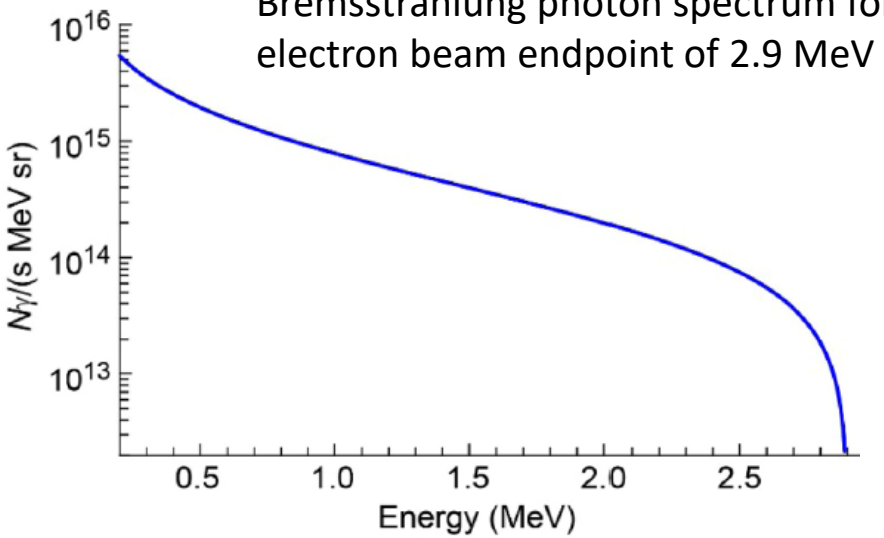
Modular
Water Cooled
Tantalum Braking Target

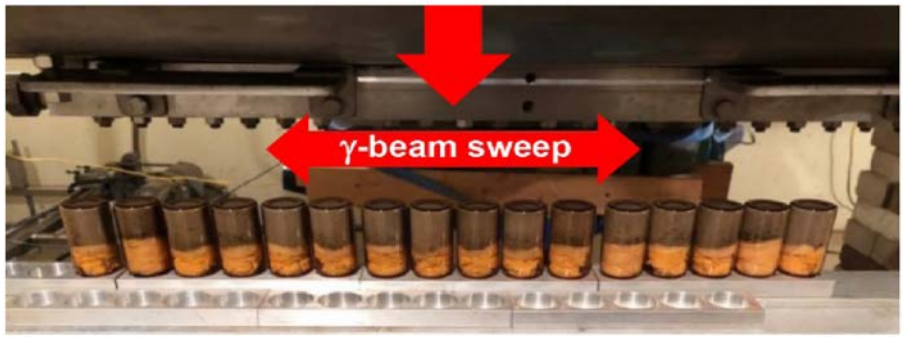
Physical Orientation of Specimens in Beam



End View

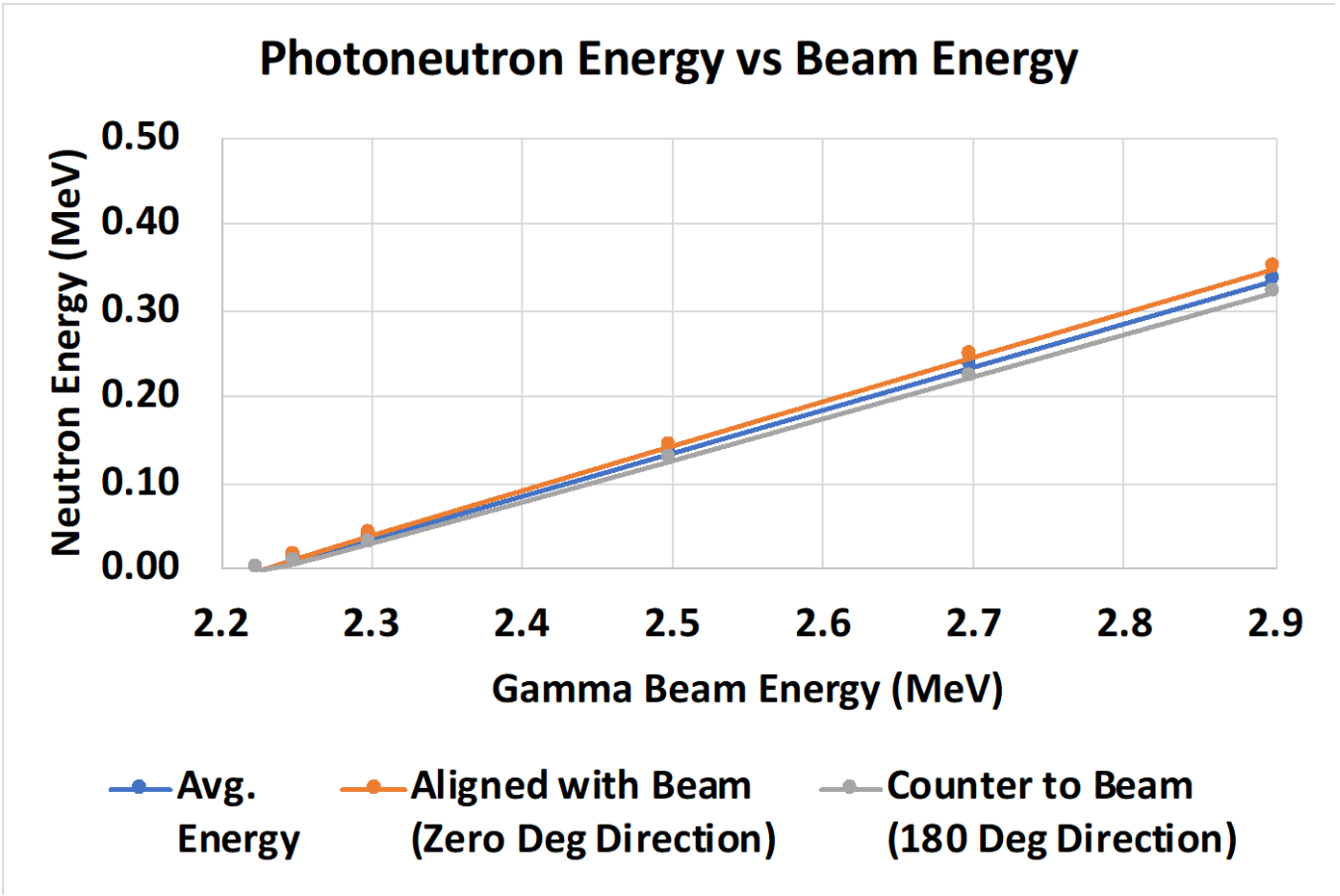
Bremsstrahlung photon spectrum for electron beam endpoint of 2.9 MeV





Specimens On Tray

Energy of "Source" Photoneutrons



All source photoneutrons below 350 keV

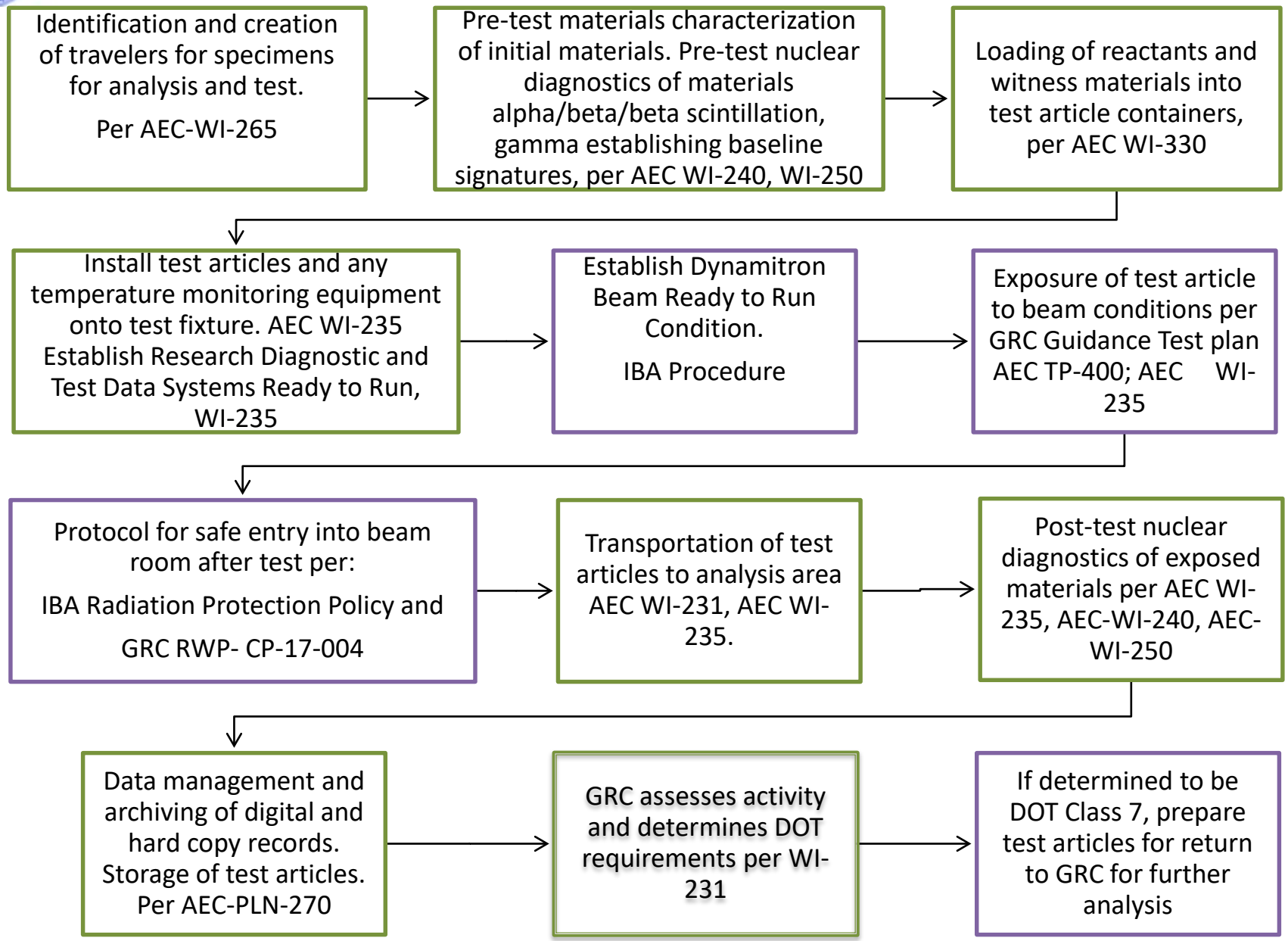
Materials Exposed

Test Shot ID	Mat'l	Duration (min)	Beam Energy (MeV)	Beam Current (mA)	Comments
Erbium					
TS1575	ErD_3	360	2.9	15	"Fueled" ErD_3 Examine Higher Z material - (Z=68)
TS1576	ErD_3	360	2.9	15	"Fueled" ErD_3 – Show repeatable process
TS589	Er, Bare	270	2.9	15	Bare Er: Baseline for ErD_3fueled shots
Titanium					
TS610-612	TiD_2	330	2.9	15	"Fueled" TiD_2 – Examine different material system, Lower Z (Z=22)
TS631	Ti, Bare	60	2.9	15	Bare Ti: Baseline for TiD_2 fueled shots

Notes:

- Case control methodology: identical tests were performed fueled vs unfueled
- For consistency between ErD_3 and TiD_2, the same amount of fuel (5E24 D_{atoms}) was exposed. 480 g of ErD_3 or 216 g of TiD_2 (exposed in 16 vials)

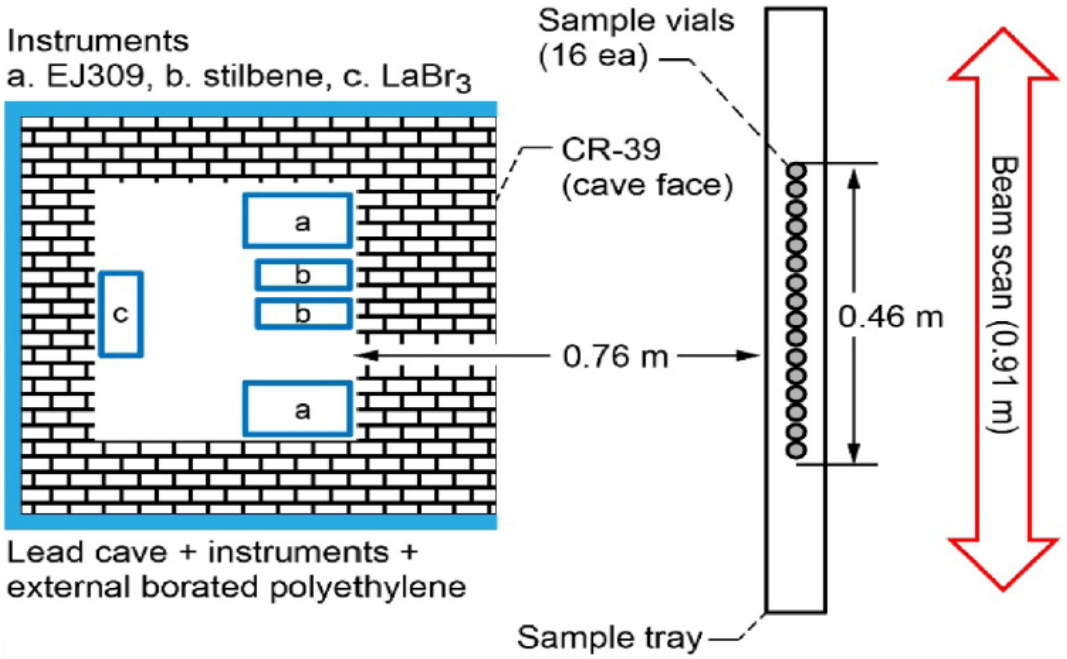
Workflow and Work Instructions





Instrumentation
Neutron Spectroscopy

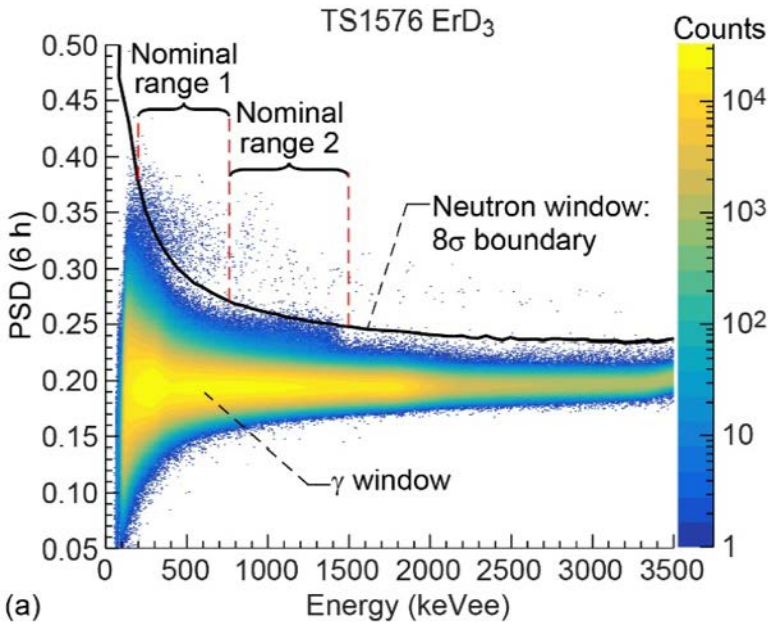
Instrumentation

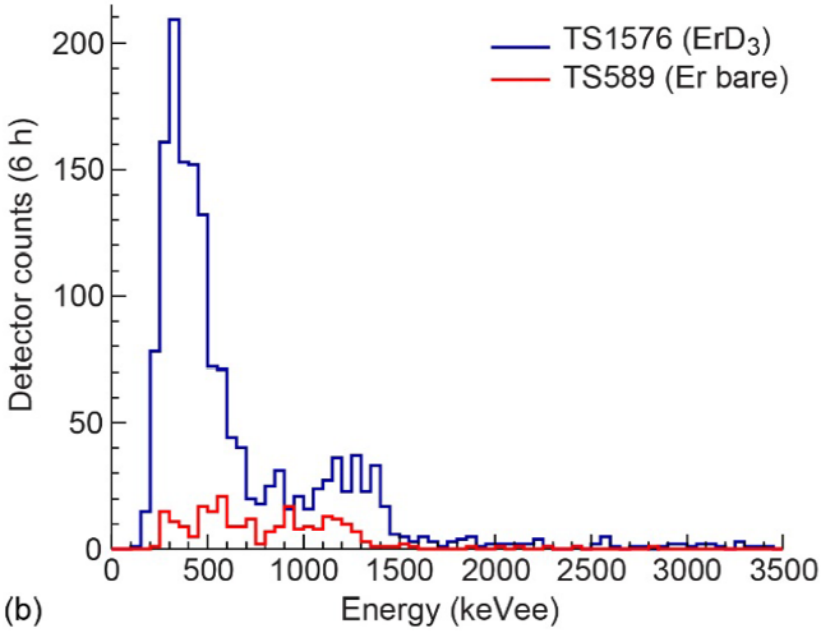


Detector	Detection technology (manufacturer)	Detector material	Detector dimensions (cm)	Location (distance from specimens) (as noted)	PMT voltage (V)	Energy detection (MeV)
Eljen-309 (HV)	Liquid Scintillator; proton recoil (Eljen)	Xylene-based liquid	5 cm diam. by 10 cm long	In cave (0.76 m)	–1,100	Neutron: 0.5 to 15
stilbene (St1)	Plastic, single crystal; proton recoil (Inrad Optics)	Stilbene crystals wrapped in PTFE tape; optically polished on face + fused silica window	2.5 cm diam. by 2.5 cm long	In cave (0.76 m)	730	Neutron: 0.3 to 15
$LaBr_3$	$LaBr_3$ detector (Canberra)	$LaBr_3$ crystal	3.8 cm diam. by 3.8 cm long	In rear of cave, rotated 90° and offset toward entry door	730	0 to 10[a]

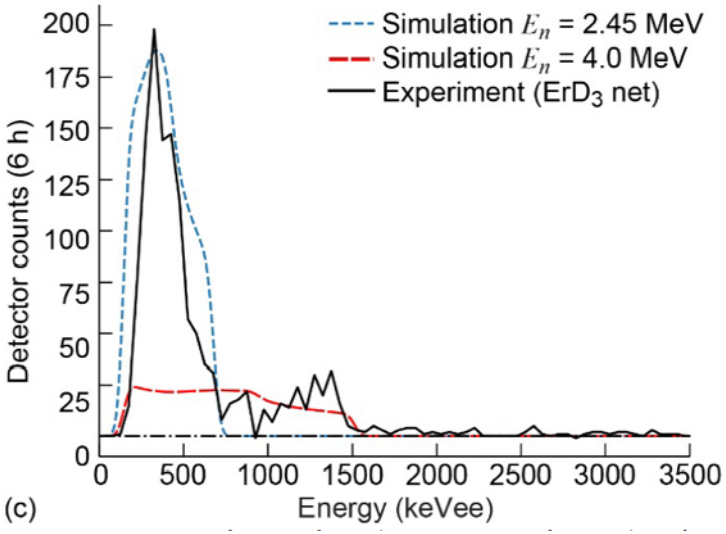
[a]Detector efficiency; gamma: ~15% for <1 MeV; ~5% for 1 to 4.4 MeV; and 0.1% for >4.4 MeV (characterization of PARIS $LaBr_3$(Ce)-NaI(Tl) phoswich detectors up to E_γ about 22 MeV, C. Ghosh, et al., *arXiv:1605.00811v2*.)

Neutron Spectroscopy: Data Post-Processing Simplified View





Ref: 8σ- 1 part in 1.6E15



Factors influencing detector efficiency: Measuring fusion (2.45 MeV) neutron counts

Detector	Detector intrinsic efficiency	Data postprocessing factors			Cave factor (neutrons passing through cave)[d]	Geometric factor[e]	Absolute detector efficiency (product)
		Filters (PU, FFT and, baseline RMS)[c]	PSD				
			Template matching	8σ			
EJ309	0.49[a]	0.65	0.88	0.42	0.20	0.0003	**7×10^{-6}**
Stilbene	0.21[b]	0.82	0.94	0.78	0.20	0.00007	**2×10^{-6}**

[a]110 keVee threshold.
[b]40 keVee threshold.
[c]PU (Pile Up), FFT (Fast Fourier Transform), RMS (root mean square).
[d]MCNP® calculations determined that the lead/B-PE cave scattered 80% of fusion energy neutrons away from the detectors permitting 20% transmission. It is noted that scattered neutrons reaching the detectors will lose less than 0.5% of their energy if scattered off of Pb nuclei.
[e]Assumes isotropic, point neutron source. Detectors located perpendicular to the beam scan direction at distance of d = 76 cm, EJ-309 detector radius, r_1 = 2.5 cm and, stilbene detector radius r_2 = 1.25 cm. Geometric scale factor: $\varepsilon_G = 1/2\left(1 - d/\sqrt{d^2 + r^2}\right)$.

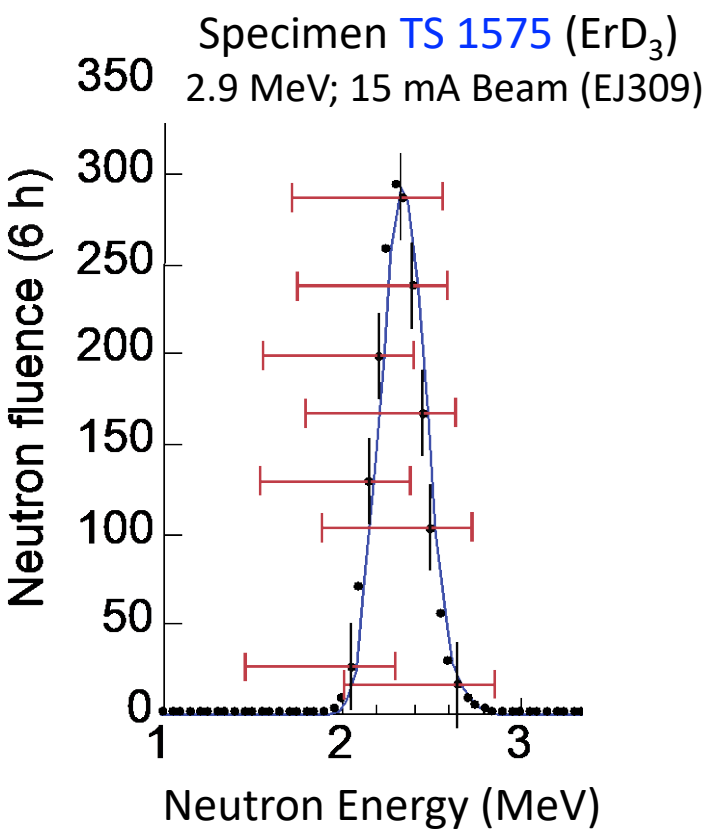
For every 1E6 fusion energy neutrons created
- EJ-309 reports ~7 neutrons
- Stilbene reports ~2 neutrons

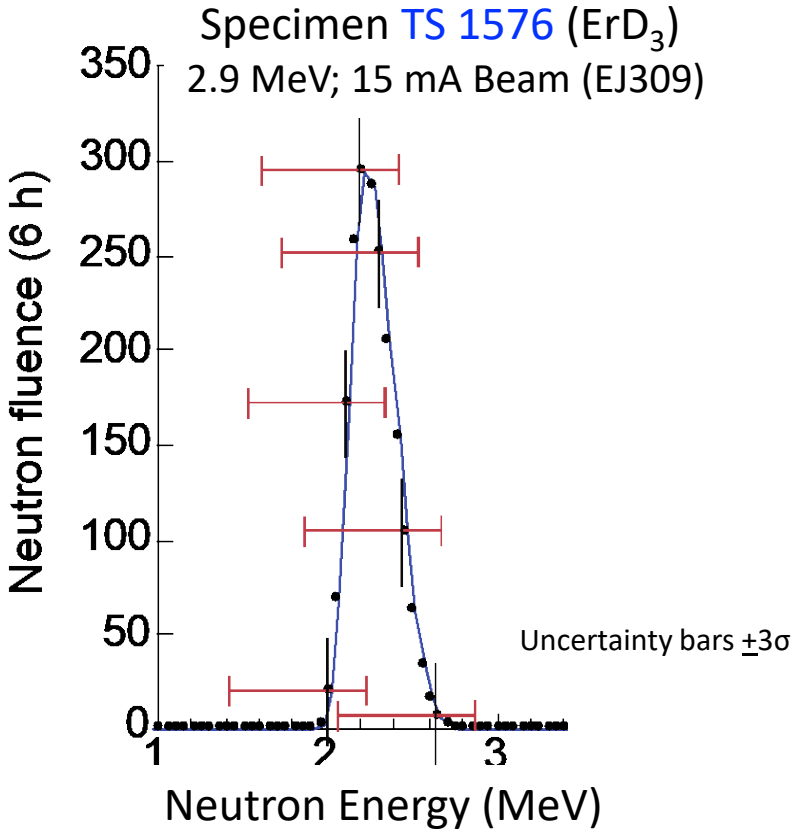


Key Results & Discussion

Evidence of Fusion Neutrons for Erbium (ErD_3)

Neutron Spectra, Net: Fueled minus unfueled



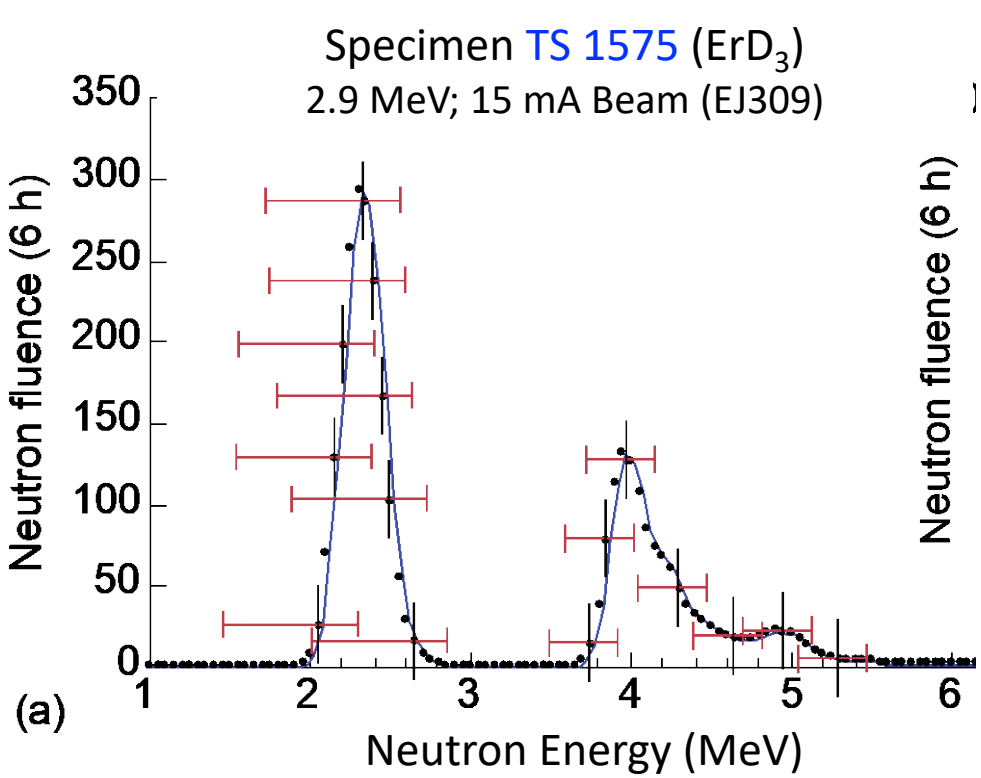


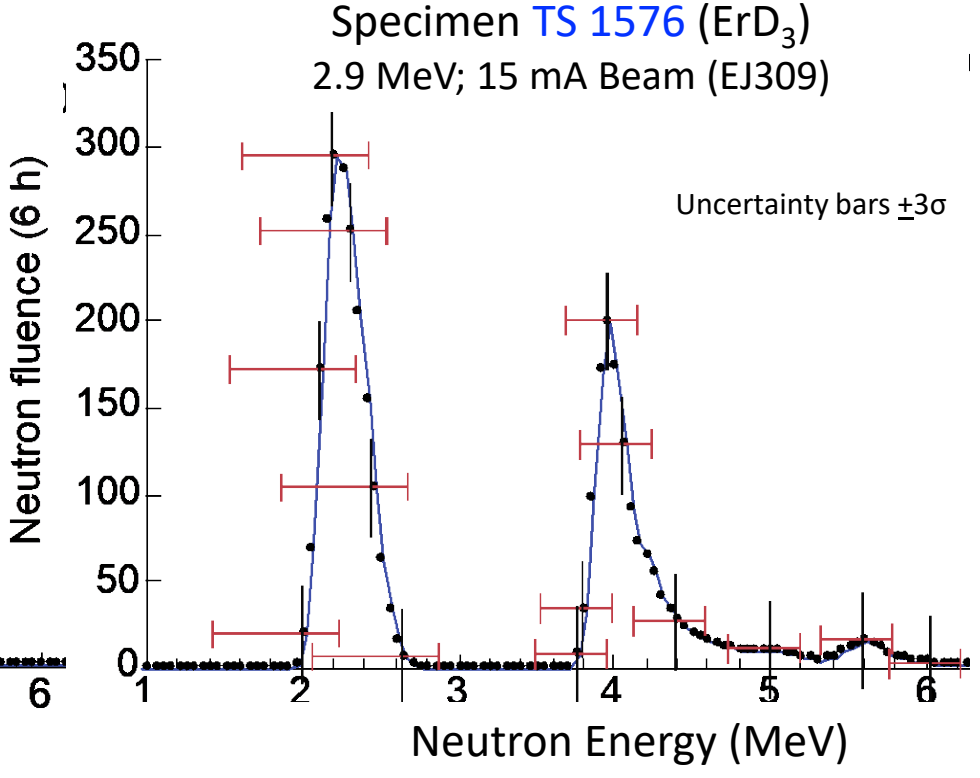
- Photodissociation max neutron energy 348 keV (2.9 MeV Gamma)
- Eljen 309 lower energy threshold 500 keV
- Fusion neutron rate ~1.5E3 cts/sec at sample tray

Clear evidence of reproducible fusion neutron process

Evidence of Higher Energy Neutrons (ErD_3)

Neutron Spectra, Net: Fueled minus unfueled





- Higher energy neutrons also recorded for both ErD_3 samples; Potential sources:
  - Neutron heating of D-fuel (Mean Free Path ~1 cm)
  - Screened Oppenheimer-Phillips Processes → energetic "n" (or "p") ejected

Clear evidence of "subsequent" nuclear reactions occurring in high density fuel

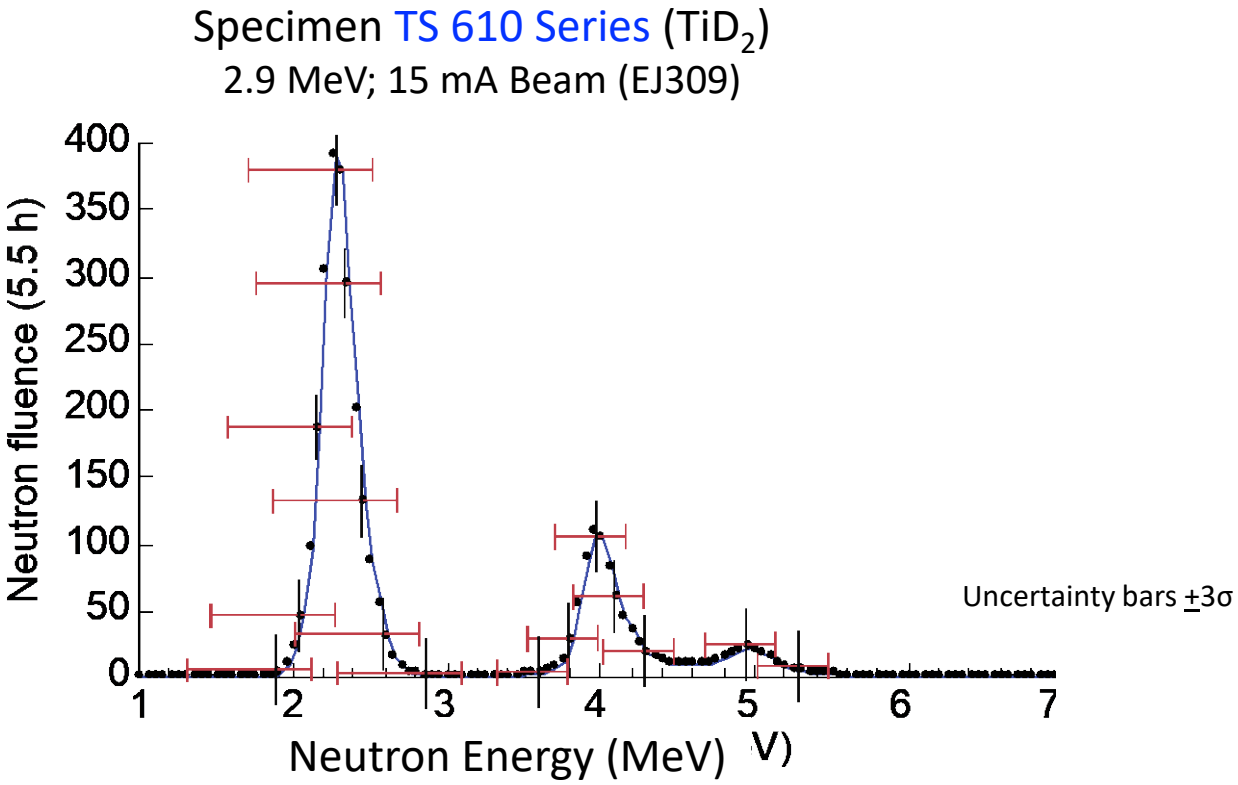
Possible Screened Reactions with Base Metal Resulting in Fast Neutron Emissions

Reaction	Base metal/natural abundance (%)	Q-value (MeV)	Projectile	Projectile energy (Mev)	Average neutron kinetic energy (Mev)	Notes: (Decay: half life)
$^{166}Er(d,n)^{167}Tm$	$^{166}Er/33.61$	2.68	d	**1.27**	**3.91**	^{167}Tm: Unstable (electron capture: 9.25 d)
$^{167}Er(d,n)^{168}Tm$	$^{167}Er/22.93$	3.09	d	1.27	4.32	^{168}Tm: Unstable (positron decay: 93 d)
$^{168}Er(d,n)^{169}Tm$	$^{168}Er/26.78$	3.35	d	1.27	4.58	^{169}Tm: Stable
$^{170}Er(d,n)^{171}Tm$	$^{170}Er/14.93$	4.17	d	**0.87**	**5.00**	^{171}Tm: Unstable (β decay: 1.92 yr)
$^{170}Er(d,n)^{171}Tm$	$^{170}Er/14.93$	4.17	d	**1.27**	**5.39**	^{171}Tm: Unstable (β decay: 1.92 yr)
$^{166}Er(^{3}He,n)^{168}Yb$	$^{166}Er/33.61$	3.50	^{3}He	**0.4**	**4.00**	^{168}Yb: Stable
$^{168}Er(^{3}He,n)^{170}Yb$	$^{168}Er/26.78$	4.63	^{3}He	**0.4**	**5.00**	^{170}Yb: Stable
$^{170}Er(^{3}He,n)^{172}Yb$	$^{170}Er/14.93$	6.01	^{3}He	0.82	6.77	^{172}Yb: Stable
$^{46}Ti(d,n)^{47}V$	$^{46}Ti/8.25$	2.94	d	**1.2**	**4.03**	^{47}V: Unstable (positron decay: 32.6 min)
$^{47}Ti(d,n)^{48}V$	$^{47}Ti/7.44$	4.61	d	**0.40**	**4.91**	^{48}V: Unstable (positron decay: 15.9 d)

[a]Bold entries correspond to reactions that may result in the neutron peaks in Figs. 5 and 6.

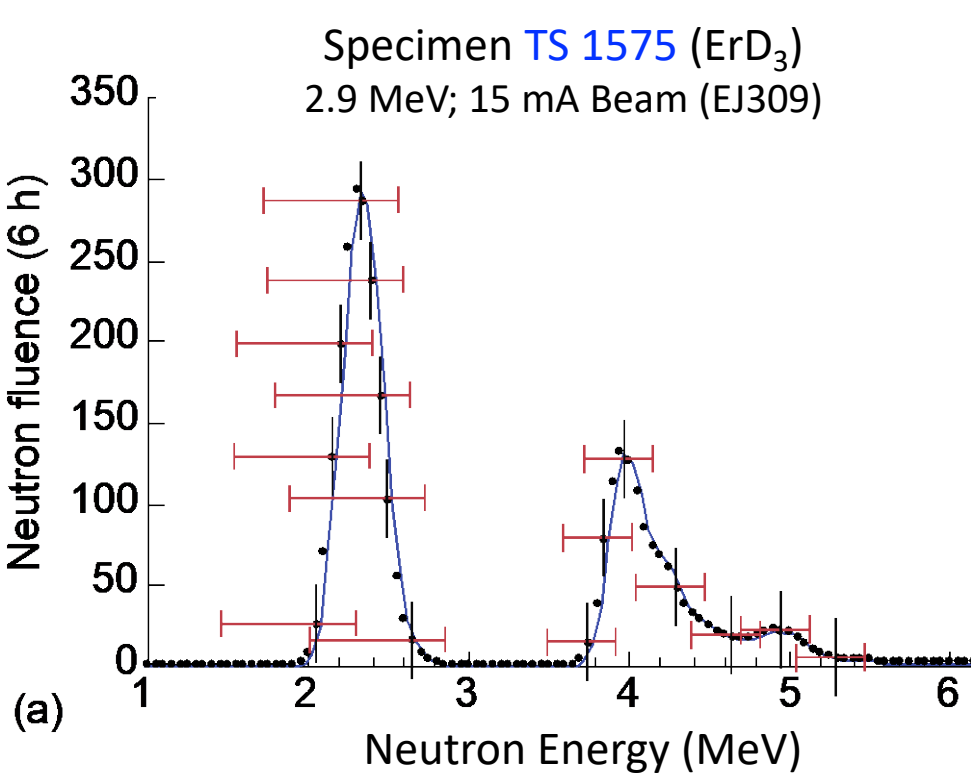
Evidence of Fusion Neutrons for Titanium (TiD_2)

Neutron Spectra, Net: Fueled minus unfueled

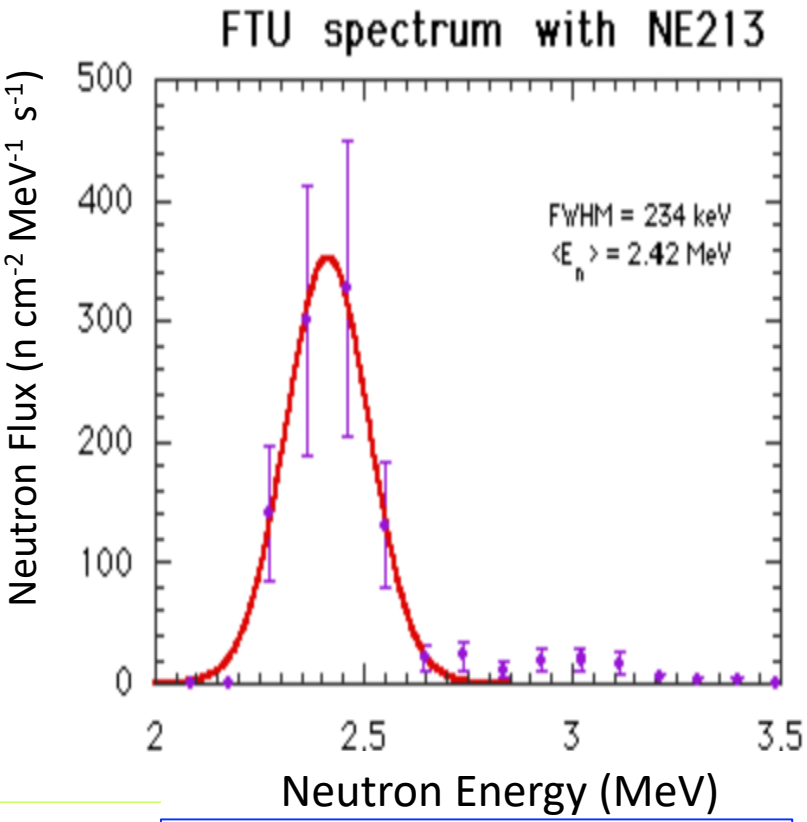


Reproducible process demonstrated with multiple materials showing both fusion energy neutrons and evidence of other processes at work

Comparison of Current n-Energy Findings to Published Fusion Studies: ENEA d-d Tokamak



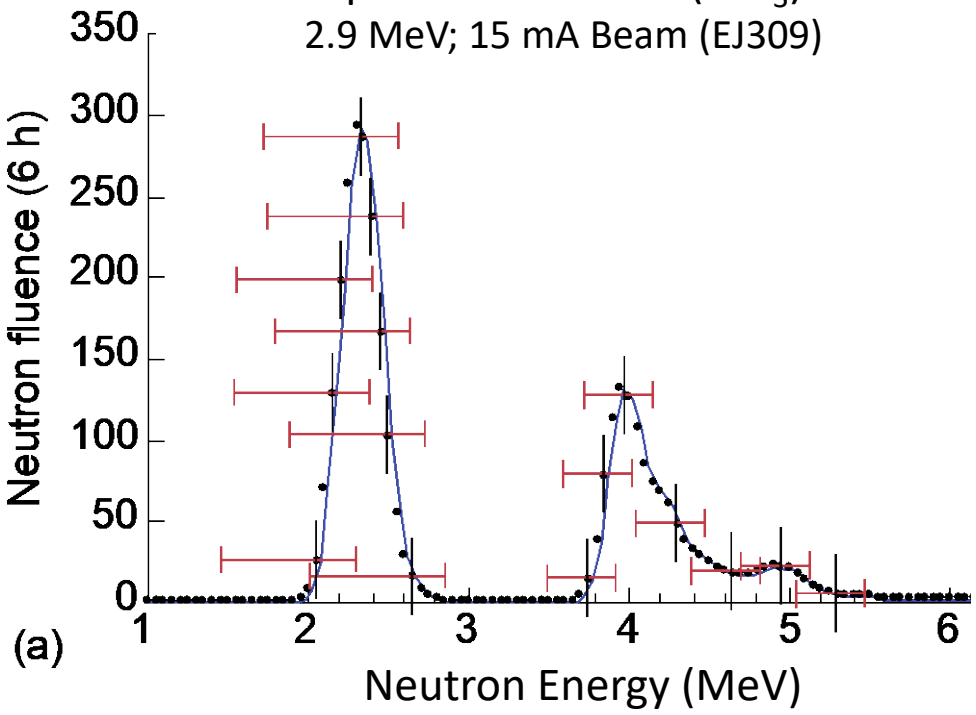
NASA (2020) Bremsstrahlung Induced Fusion Results



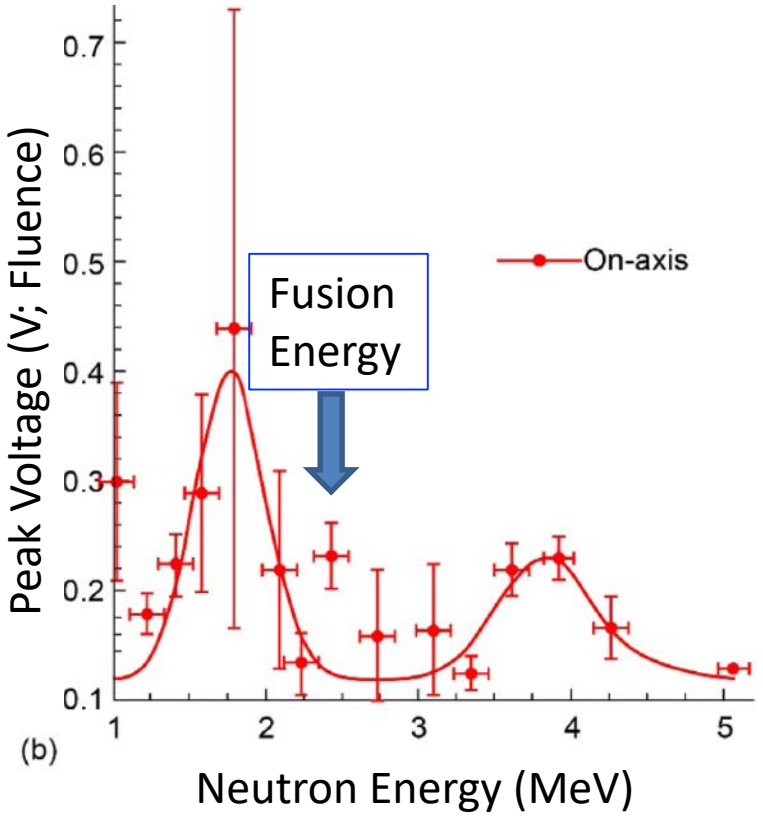
Magnetic Confinement Fusion

Ref: "Neutron spectrum in FTU ohmic discharges" section 6, Fig. 10, https://www.afs.enea.it/basilio/neutronica/Neutroni.htm

Comparison of Current n-Energy Findings to Published Fusion Studies: Mori Laser Fusion



NASA (2020) Bremsstrahlung Induced Fusion Results



LASER Inertial Confinement Fusion

Ref: Y. Mori et al., Nucl. Fusion 57, 116031 (2017)

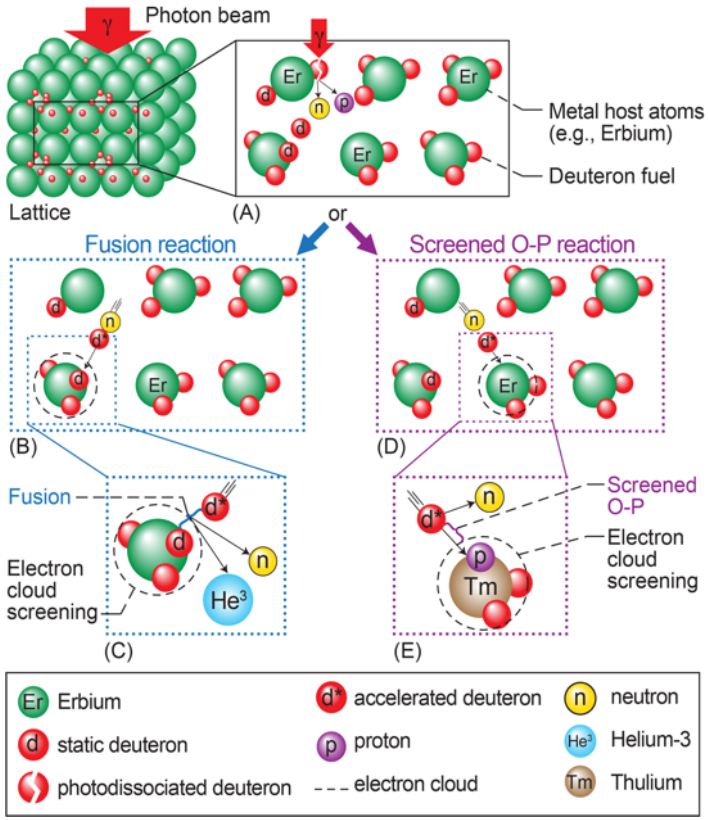
Comparison of Measured and Theoretical Calculations

- d-D fusion rates in the highly screened environment were calculated using the methods to be outline in Theory Section
- Key Equations were programmed into Mathematica
- Solution proceeded along the following steps:
  - Calculate bremsstrahlung spectrum flux from 0–2.9 MeV, using the five-term β function approximation with a 2.9-MeV endpoint
  - Calculate the photoneutron energy spectra; (for heating d)
    - Average photoneutron energy of 145 keV
  - Determine the resulting deuteron energy spectra
    - Average hot deuteron energy of 64 keV
  - Determine the number of d-D reactions per second
- Utilizing both shell and plasma screening (with screening length $\lambda sc = 4.16 \times 10^{-10}$ cm), we calculate a total reaction rate for all 16 samples of 1.2×10^3 neutrons/s.
- Measured Rate: 1.5×10^3 neutrons/s at sample tray

Excellent correlation between measured and predicted fusion rates

Summary: Key Findings

- Current tests investigated the feasibility of initiating fusion reactions with simple, relatively inexpensive equipment
  - "Globally Cold - Locally Hot" Environment
- Demonstrated the impact of efficient electron screening on localized fusion rates in a dense fuel environment
  - Screening provided by shell, conduction, or plasma electrons
- Exploited neutrons to effectively heat deuterons in primary and subsequent reactions with the well-screened cold target fuel
- Performed fusion cycle at high fuel density inside a metal lattice, which enables subsequent reactions with the host metal nuclei and other secondary processes



Future Work

- Experiments should be repeated with a pulsed beam (using time-of-flight neutron spectroscopy) to
  - further validate the d -D fusion reactions
  - further resolve the source of the higher-energy neutrons
- Using a precision pulsed *γ* beam one could
  - Control neutron and deuteron energies to examine primary and boosted fusion and screened O-P processes over a wide energy range
  - Examine nuclear cross sections as a function of beam/deuteron energy and host materials
- Process scale up using an energy-efficient LINAC, may lead to a new means of a new heat source; generating or boosting medical and industrial isotope



Questions?

I/O Tool

https://arc.cnf.io/sessions/z7mg/#!/dashboard



Break

15 Minutes

LCF Workshop: Theory Paper

Dr. Vlad Pines and Dr. Arnon Chait
Theoretical Physicist and Senior Scientist
NASA GRC



"Nuclear fusion reactions in deuterated metals"

Vladimir Pines, Marianna Pines, Arnon Chait, Bruce M. Steinetz, Lawrence P. Forsley, Robert C. Hendricks, Gustave C. Fralick, Theresa L. Benyo, Bayarbadrakh Baramsai, Philip B. Ugorowski, Michael D. Becks, Richard E. Martin, Nicholas Penney, and Carl E. Sandifer, II



Phys. Rev. C 101, 044609 – Published 20 April 2020
https://journals.aps.org/prc/abstract/10.1103/PhysRevC.101.044609

Nuclear Fusion Reactions in Deuterated Metals

- Introduction
  - Conventional Tokamak Hot Fusion vs. LCF Process
- Lattice Confinement Fusion: Theory
  - Background
    - Nuclear fusion cross-section & screened coulomb potential energy
  - Nuclear Fusion with Electron Screening: (lattice screening, plasma, conduction electrons)
  - Coulomb Scattering on Target Nuclei: Importance of large angle scattering to achieve fusion
  - Neutron elastic scattering on deuteron nuclei
  - Neutron energy loss in elastic collisions with deuteron nuclei
- Question/Answer Tool Open
  - https://arc.cnf.io/sessions/z7mg/#!/dashboard

Conventional Tokamak Hot Fusion vs. LCF Process

$$R \sim n_1 n_2 \sigma v$$

To increase R:

- Increase density of reactants ($n_1 n_2$)
- Increase reaction cross-section (σ)

Reaction Rate (#/sec/cm^3)	=	Large angle scattering probability	x	Nuclear tunneling probability	x	Projectile n1 (#/cm^3)	x	Target n2 (#/cm^3)
Conventional hot fusion		Very Low		Low (keV)		Projectile Hot Low (10^14/cm^3)		Target Hot Low (10^14/cm^3)
LCF fusion process		High		High (keV-MeV)		Projectile Hot Very Low (10^10/cm^3)		Target Cold Very High (10^22/cm^3)

Lattice Confinement Fusion: Theory

- What is different about LCF?
  - Electrostatic screening (shell, conduction electrons, plasma)
  - Presence of lattice nuclei
  - Explicit utilization of neutral particles in the reaction process

- Unpacking the fusion process:
  - Scattering events, the role of small vs. large angle scattering, and presence of screening
  - Nuclear tunneling under the presence of screening
  - Energy transfer upon collision
  - Adding the above – what is the preferred combination to induce D-D fusion?
    - Light charged particle on D
    - Heavy charged particle on D
    - Photon on D
    - Neutron on D

- Other practical considerations: Effect of lattice metal atoms

Reminder: Nuclear Fusion Cross-Section

Nuclear fusion cross-section:

$$\sigma_{\text{bare}}(E) = \frac{S(E)}{E} \exp\left[-G(E)\right]$$

The Gamow Factor (WKB Approximation):

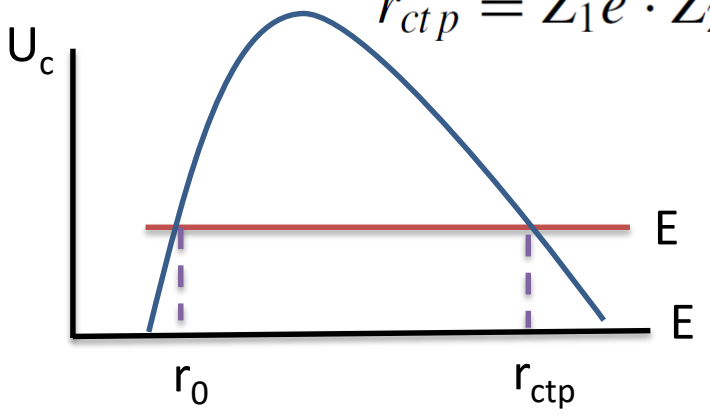
$$G(E) = \frac{2}{\hbar}\int_{r_0}^{r_{ctp}} \{2\mu[U_C(r) - E]\}^{1/2} dr$$

The Coulomb potential energy:

$$U_C(r) = Z_1 e Z_2 e / r$$

$$r_0 = (R_1 + R_2)$$

$$r_{ctp} = Z_1 e \cdot Z_2 e / E$$



Electron Screening in Coulomb Energy

The screened Coulomb potential energy:

$$U_{C,\,\mathrm{sc}}(r) = \frac{Z_1 e Z_2 e}{r} \exp\left(-\frac{r}{\lambda_{\mathrm{sc}}}\right)$$

For a radial distance:

$$r_0 \leqslant r \leqslant r_{ctp} \ll \lambda_{\mathrm{sc}}$$

Following expansion, the screened Coulomb energy is reduced to :

$$U_{C,\mathrm{sc}}(r) = \frac{Z_1 e Z_2 e}{r}\left(1 - \frac{r}{\lambda_{\mathrm{sc}}}\right) = U_C(r) - U_e$$

The electron screening potential energy:

$$U_e = \frac{Z_1 e Z_2 e}{\lambda_{\mathrm{sc}}}$$

Types of Electron Screening

- Screening could be provided by shell, conduction, or plasma electrons:

$$\lambda_{TF} = a_{TF} = \frac{1.4a_0}{Z^{1/3}}; \qquad \lambda_{SC} = \left(\frac{kT_e}{4n_{eD}e^2}\right)^{1/2}$$

- Conveniently, screening effect is expressed via a negative uniform shift of the Coulomb barrier:

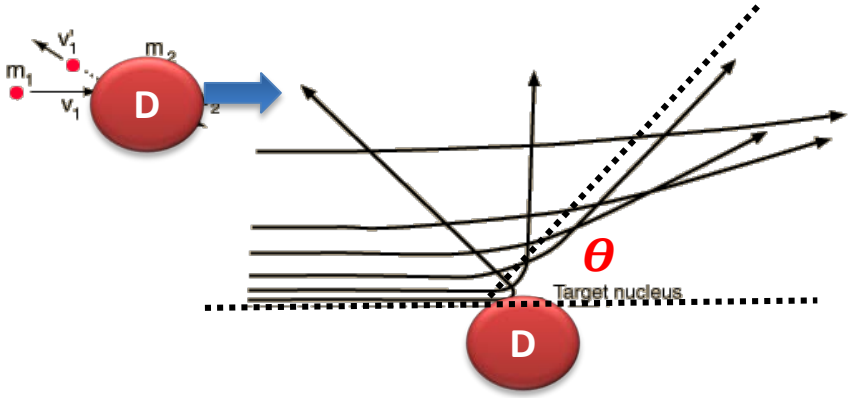
$$\sigma_{\exp}(E) = \sigma_{\text{bare}}(E) f(E)$$

$$f_{U_e}(E) = \frac{E}{(E+U_e)} \exp\left[G_C(E) - G_C(E+U_e)\right]$$

- For example:
  - For D shell electron: $\lambda_{TF} = 7.4 \cdot 10^{-9} cm\,; \quad U_e = 20eV$
  - For lattice (conduction) electrons:

$$\lambda_{sc} = 4.8 \cdot 10^{-10} cm\,; \quad U_e = 300eV$$

Small vs. Large Coulomb Scattering Angles



Scattering cross section

↑∞

Nuclear reaction probability

0

π/2

π

Scattering Angle

Nonproductive Small Angle Scattering Always Dominate in Coulomb Scattering (1)

- For any nuclear reaction we need large angle scattering, whose relative probability to total scattering is:

$$P_{sc}\left(\pi/2 \le \theta \le \pi\right) = \frac{\int_{\pi/2}^{\pi} \left.\frac{d\sigma}{d\Omega}\right|_{d-D} \cdot 2\pi \cdot \sin\theta d\theta}{\sigma_{d-D}}$$

- Decreasing screening length increases the probability of large angle scattering, in which nuclear reactions are possible through tunneling

$$\left.\frac{d\sigma}{d\Omega}\right]_{d-D} \sim \frac{1}{\left(\Theta^2+\Theta_{min}^2\right)^2} \qquad \theta_{\min,p} = \frac{\hbar/\lambda_{\mathrm{TF}}}{p_p} \sim \frac{1}{a_{TF}}$$

- The total cross section becomes:

$$\sigma_{d-D} = \int \left.\frac{d\sigma}{d\Omega}\right|_{d-D} d\Omega \approx \frac{\pi D_{d-D}^2}{\theta_{\min,d}^2}$$

Nonproductive Small Angle Scattering Always Dominate in Coulomb Scattering (2)

- Example: for d-D collision at 3 *MeV*
  - Total cross section: 11.5 Mb
  - The probability of large angle scattering, when screened by shell electrons:

$$P_{sc}(\pi/2 \leqslant \theta \leqslant \pi) = 1.57 \times 10^{-10}$$

and by conduction electrons:

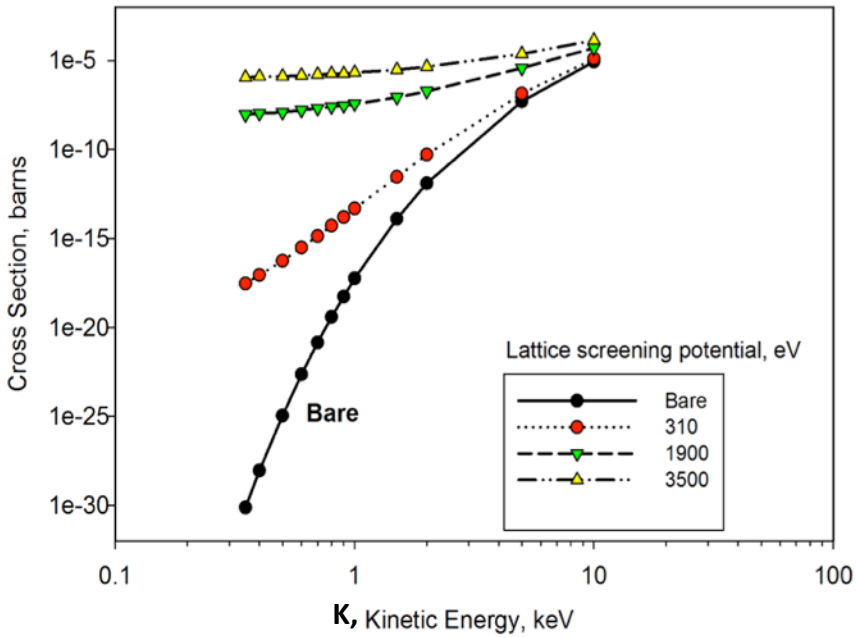
$$P_{sc}(\pi/2 \leqslant \theta \leqslant \pi) = 3.45 \times 10^{-8}$$

- Example: for d-D collision at 10 *keV*
  - Total cross section: 3.45 Gb
  - P(large angle, shell) = 4.7×10^{-8}
  - P(large angle, conduction) = 1×10^{-5}

Overall Effect of Screening

- Effect of screening on nuclear tunneling diminishes with increasing energy:
- However, screening effect on large angle scattering probability, p, is not reduced with increasing energy:
  - p(conduction)/p(shell) = 220 for both 10keV and 3 MeV
- The overall number of nuclear events increase with enhanced screening

Cross Section vs Kinetic Energy



Energy Transfer Upon Collision: Small Angle Dominance for Charged Particles

- Mean recoil energy in single electron-deuteron collision

$$\bar{E}_N = \frac{\hbar^2}{m_N \lambda_{TF}^2} \times \frac{\left\{(2+\alpha)(1+\alpha\beta^2)\ln\left(\frac{2+\alpha}{\alpha}\right) - 2[1+(1+\alpha)\beta^2]\right\}}{2(2+\alpha\beta^2) - \alpha(2+\alpha)\beta^2 \ln\left(\frac{2+\alpha}{\alpha}\right)}$$

where $\alpha = \theta_{\min}^2/2, \ \beta = v_e/c$.

- Mean recoil energy in single charged heavy particle collision

$$\bar{E}_N(\beta_p \ll 1) = \frac{\hbar^2}{m_N \lambda_{\mathrm{TF}}^2} \ln\left(\frac{2}{\theta_{\min,p}}\right) = \frac{\hbar^2}{m_N \lambda_{\mathrm{TF}}^2} \ln\left(\frac{2\lambda_{\mathrm{TF}}}{\hbar}\right)\sqrt{2m_p E_p})$$

since $\theta_{\min,p} = \hbar/(\lambda_{\mathrm{TF}} p_p) = \hbar/(\lambda_{\mathrm{TF}}\sqrt{2\,m_p E_p}) \ll 1.$

Energy Transfer Upon Collision: Independence of Small Angle for Neutral Particles

- Mean recoil energy in single photon-deuteron collision

$$\bar{E}_D = E_\gamma \left[2\varepsilon_D \left(9 + 51\varepsilon_D + 93\varepsilon_D^2 + 51\varepsilon_D^3 - 10\varepsilon_D^4 \right) \right.$$
$$\left. - 3(3 - \varepsilon_D)(1 + \varepsilon_D)(1 + 2\varepsilon_D)^3 \ln(1 + 2\varepsilon_D) \right]$$
$$\times \{ 6\varepsilon_D (1 + 2\varepsilon_D)[2 + \varepsilon_D (1 + \varepsilon_D)(8 + \varepsilon_D)]$$
$$- 3(1 + 2\varepsilon_D)^3 [2 + \varepsilon_D (2 - \varepsilon_D)] \ln(1 + 2\varepsilon_D) \}^{-1}$$

$$\varepsilon_D = \frac{E_\gamma}{m_D c^2}$$

- Mean recoil energy in single neutron-deuteron collision

$$\bar{K}'_d = K_n - \bar{K}'_n = \frac{1}{2}(1 - \alpha_n) K_n$$
$$= \frac{2 m_n m_d}{(m_n + m_d)^2} K_n = \frac{4}{9} K_n,$$

- = ½ max energy in head-on collision

$$K'_{d,\max} = \frac{4 m_n m_d}{(m_n + m_d)^2} K_n$$

Neutral Particles: The Workhorse of LCF Fusion Reactions

TABLE II. Mean deuteron recoil energies for various reactions.

Reaction (*particle*, D)		Total cross section, σ (barn)	Mean deuteron recoil energy
Light particles (e^-, e^+)	$E_e = 2$ MeV	38.41 kb	24.75 meV
Heavy particles	$E_p = 3$ MeV	5.76 Mb	41.4 meV
	$E_d = 3$ MeV	11.51 Mb	42.7 meV
	$E_\alpha = 3$ MeV	91.48 Mb	44 meV
Compton γ	$E_\gamma = 2$ MeV	49.43 nb	2.13 keV
Neutron, n	$E_n = 2.45$ MeV	3 b	1.09 MeV

Effect of Lattice Metal Atoms

- We want maximum number of scattering events on the fuel – not on lattice host atoms:

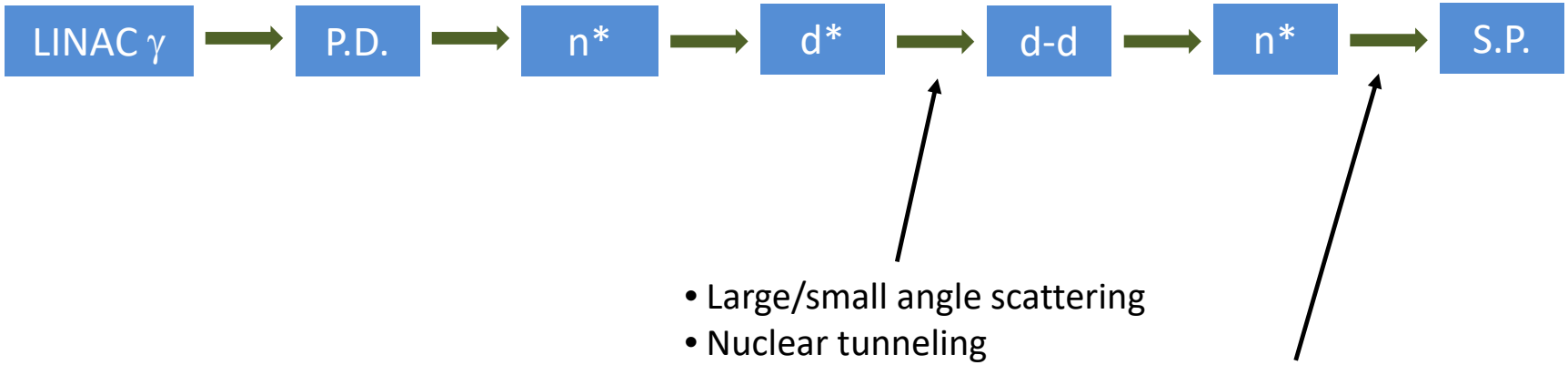
$$d_R(E_D) = \frac{\sigma_{d-D}^{total} \cdot N_D}{\sigma_{d-D}^{total} \cdot N_D + \sigma_{d-host}^{total} \cdot N_{host}} \cdot d(E_D) =$$

$$= \frac{1}{1 + \left(\sigma_{d-host}^{total} / \sigma_{d-D}^{total}\right)\left(N_{host} / N_D\right)} \cdot d(E_D) = \frac{1}{1 + Z_{host}^2 \cdot c_R} \cdot d(E_D)$$

$d_R(E_D)$ is the fraction of hot deuterons available for D-D fusion reaction. $d(E_D)$ is the total pool of hot deuterons

- But this is counteracted by Oppenheimer-Phillips stripping reaction, in which screening could be very important in high Z number

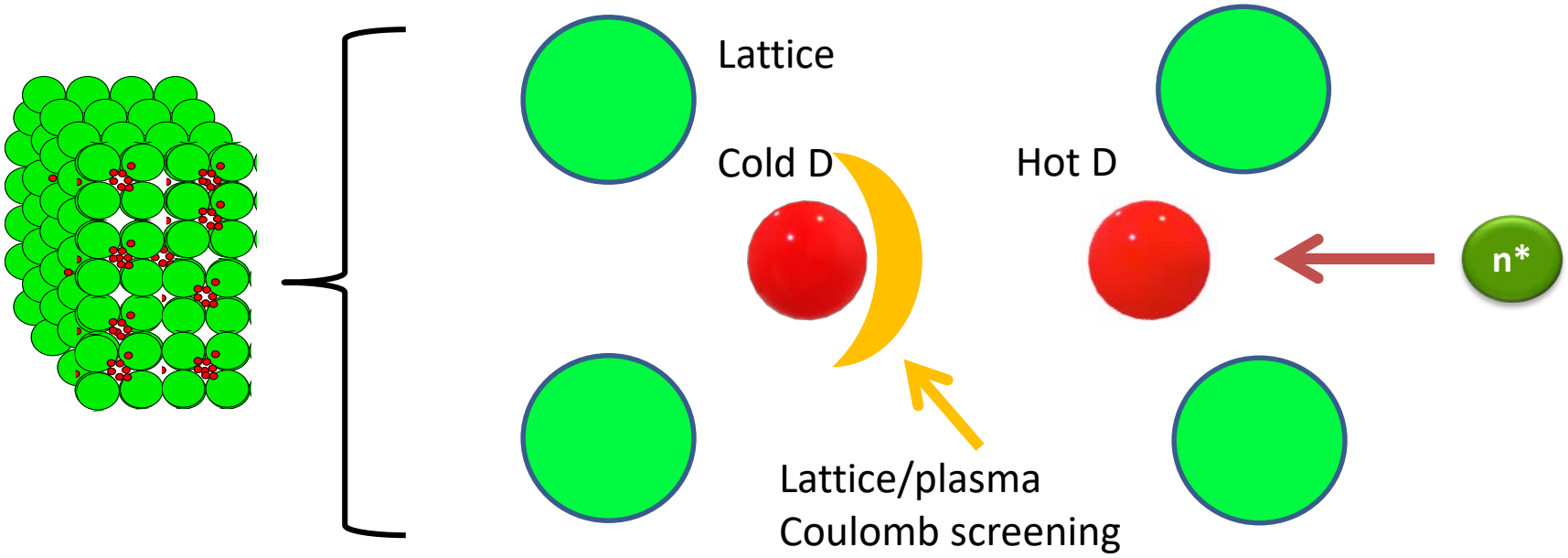
Theory At a Glance



Also:

- Unified formulation of all screening types: shell, conduction, plasma channels created by gamma and Compton electrons
- Increase in astrophysical factor S(E) due to screening independently of its effect on tunneling
- Large/small angle scattering with screening for light/heavy charged particles and for neutrons
- Kinematic equations for calculations of all reaction product energies including subsequent events

Lattice Confinement Fusion: Process Description



- Reactions are highly localized: majority of the fuel is **cold**
- D-D interactions are highly screened: **most favorable large/small angle scattering probability** → highest nuclear tunneling probability
- Most efficient means to heat fuel – **neutrons** – for high tunneling probability
- **Only use energy to heat the projectile D, not the entire fuel D**
- **Process control is possible** through:
  - Number and energy of neutron source: fusion process is **not self-sustainable**
  - Customizing fuel and lattice elements



Questions?

I/O Tool

https://arc.cnf.io/sessions/z7mg/#!/dashboard

LCF Workshop: Panel Session

Dr. Theresa Benyo, Panel Moderator
Analytical Physicist, Materials & Structures Division
NASA GRC



NASA Glenn Research Center
Advanced Energy Conversion Team
May 21, 2020

Panel Members:
Matt Forsbacka NASA HQ, Michael Houts NASA MSFC,
Ron Litchford NASA HQ, John Scott NASA- JSC

LCF Panel Session Introduction

- LCF Workshop Objective 2
  - Invite feedback from invited panelists regarding the work presented.
- Key Discussion Topics for Panelists
  - Comments on experiments
  - Comments on theory
- Panelist Introductions
  - Dr. Matthew Forsbacka
  - Dr. Michael Houts
  - Dr. Ron Litchford
  - Mr. John Scott
- Moderated Discussion: Q/A
  - I/O tool: https://arc.cnf.io/sessions/z7mg/#!/dashboard

Panelist Introductions



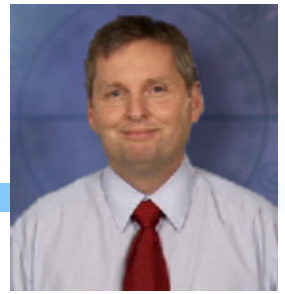
- Dr. Matt Forsbacka (NASA HQ)
  - Director, Safety Assurance and Requirements Division (SARD)
    - Leads the SARD team of subject matter experts
  - Past assignments
    - Nuclear Flight Safety Assurance Manager within SARD
    - Senior Executive at the Defense Nuclear Facilities Safety Board
    - Program Director for human portable radiation detection systems at the Dept of Homeland Security
  - B.S., M.S. in Nuclear Engineering from Univ of Florida
  - Ph.D. in Nuclear Engineering from Univ of Virginia

Panelist Introductions



- Dr. Michael Houts (NASA MSFC)
  - Principal Investigator for Nuclear Thermal Propulsion
    - Nuclear Research Manager: provides guidance and technical advice on research and development related to the design, development, and utilization of space nuclear power and propulsion systems
  - Past assignments
    - Team Leader for Criticality, Reactor, and Radiation Physics, Deputy Group Leader at Los Alamos National Laboratory
  - BSME & BS Nuclear Engineering from Univ of Florida
  - PhD in Nuclear Engineering from MIT

Panelist Introductions



- Dr. Ron Litchford (NASA HQ)
  - Principal Technologist, Game Changing Development Program in Office of the Chief Technologist
    - Aerospace propulsion and power systems and advanced energy applications
  - AIAA Assoc Fellow, Vice-Chair/Chair-Elect of AIAA's Plasmadynamics and Lasers Technical Committee, and a member of the International Liaison Group for MHD and High Temperature Technologies
  - Past assignments
    - Research Engineer with the UT-Calspan Center for Space Transportation and Applied Research
    - Project Manager for ERC Inc.
  - BSME, Tennessee Technological Univ
  - MSME and PhD (Aerospace Engineering), Univ of Tennessee Space Inst

Panelist Introductions



- Mr. John H. Scott (NASA JSC)
  - Chief Technologist for the Propulsion and Power Division
    - Responsible for advancing the technology needed by Human Spaceflight
  - Past assignments
    - Project mgr and supervisor in support of Space Shuttle, International Space Station, and various Human Exploration study programs
    - Aerospace Engineer at TRW
  - Published articles on spacecraft fuel cell and nuclear power technologies.
  - BSME from Rice University
  - MSME and MBA from UCLA

Panel Questions: John H Scott NASA-JSC/EP

- Theory Paper
  - Energy Balance: There is no discussion of the nucleon-level energy balance (photon to hot neutron to deuteron to D-D fusion product) nor of the effect of multiplication (e.g., how many D-D fusion products per incident photon).
  - Significance of Lattice Screening Potential in Enhancement of Reactions: If U_e for ErD_3 is only 347 eV, of what significance is that in reaction enhancement when the D-D fusion cross section peaks at ~700 keV?

- Experimental Paper
  - Neutron Spectrum: The neutron energy output energy measured is indeed consistent with the neutron product energy of D-D fusion. It is also only slightly below the energy of the incident photons. What evidence is there that we are getting D-D fusion at all, as opposed to the photon energy going straight into photodissociated neutrons?
  - Can any measurements be made in future experiments to collect other potential fusion products (e.g., *p,* ^{4}He, etc.)? Could the temperature of the samples and fixtures be measured to enable a bulk energy balance?



Questions?

I/O Tool

https://arc.cnf.io/sessions/z7mg/#!/dashboard

Lattice Confinement Fusion (LCF) Workshop

Going Forward

Lawrence Forsley
Senior Lead Experimental Physicist
Global Energy Corporation

NASA Glenn Research Center

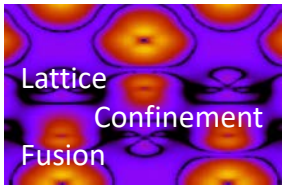
Advanced Energy Conversion Team

May 21, 2020



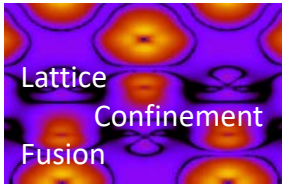


Going Forward



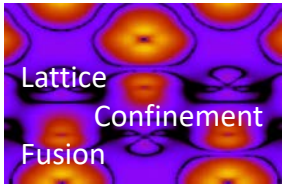
- Goal
- The Path
  - Modeling
  - Neutron Heating and Fusion
  - Electron Screening
  - Comparing Fusion Methods
  - Related Research
- In Conclusion

Goal



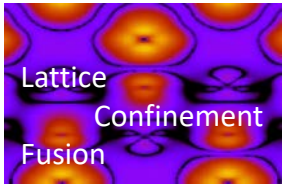
- The PRC papers demonstrate Lattice Confinement Fusion.
- The goal is to further understand LCF through modeling, experiments and analyses to scale a new power source for deep space and terrestrial power.
- That understanding will lead to gain and scaling, necessary for useful engineering and application.

The Path: *Modeling*

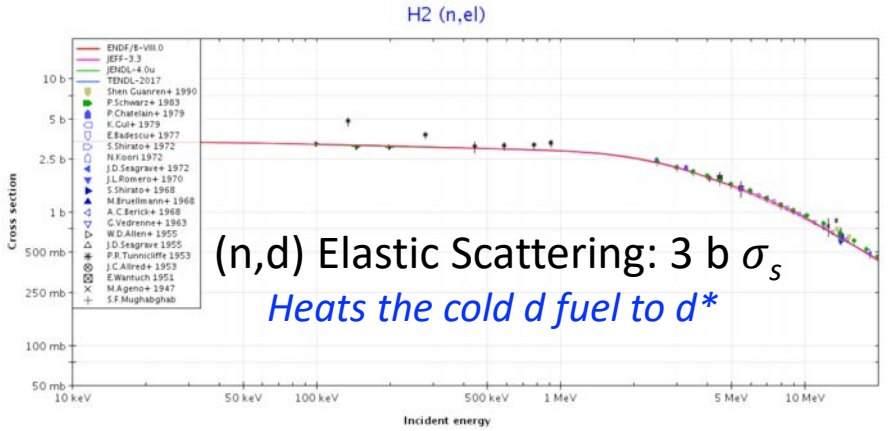


- Model the interaction of charged and neutral particles with the lattice and each other.
  - *Unfortunately, neither LANL MCNP nor CERN GEANT-4 Monte Carlo nuclear codes handle heavy charged particles < 1 MeV nor electron screening.*
  - *Fortunately, we acquired MCNP subroutines designed for ITER to properly handle DD, DT and D^3He fusion from 10 keV- 50 keV using SRIM/TRIM tables.*
  - *The addition of the PRC Theory Paper enhancement factor, f(E), should allow modeling these reactions with electron screening down to an effective 1 keV deuteron kinetic energy.*
  - This can be tested against Lawrence Berkeley National Laboratory plasma discharge 1.2 keV c.m. *Ion*$_T$ fusion results.

The Path: *Neutron Heating and Fusion*

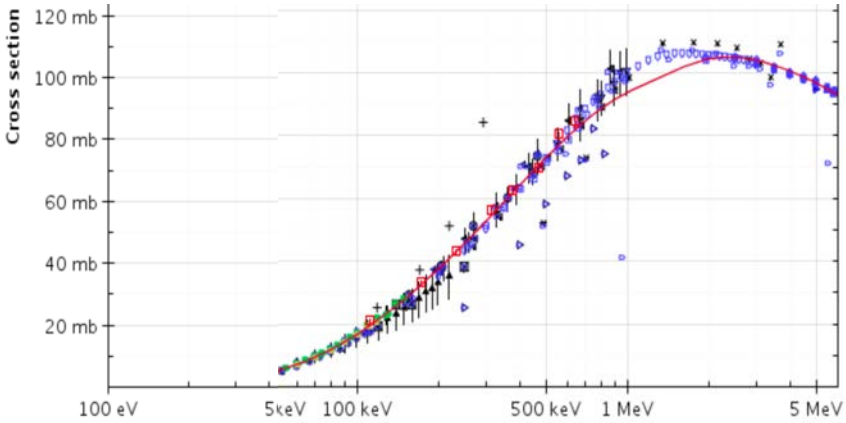


- The neutron mean-free path at various energies defines the size of the prospective reactor.
- The lattice materials influence neutron:
  - Mean-free path via density and scattering cross-sections
  - Energy by the same
  - Capture cross-sections
- Both MCNP and GEANT-4 codes handle neutron energies from thermal (.025 eV) to > 20 MeV
- Modeling predicts the neutron economy
  - *Not unlike conventional reactors*



(n,d) Elastic Scattering: 3 b σ_s

*Heats the cold d fuel to d**



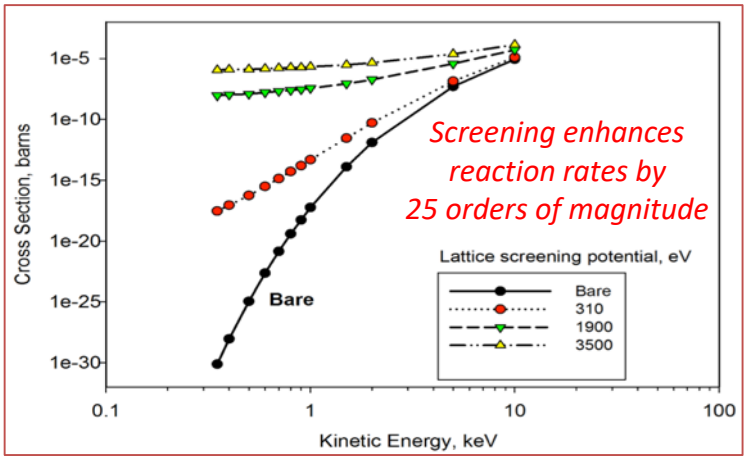
d*d Fusion: < 20 mb to 100 mb σ_f

Electron screening increases probability!

JANIS tables

The Path: *Electron Screening [1]*

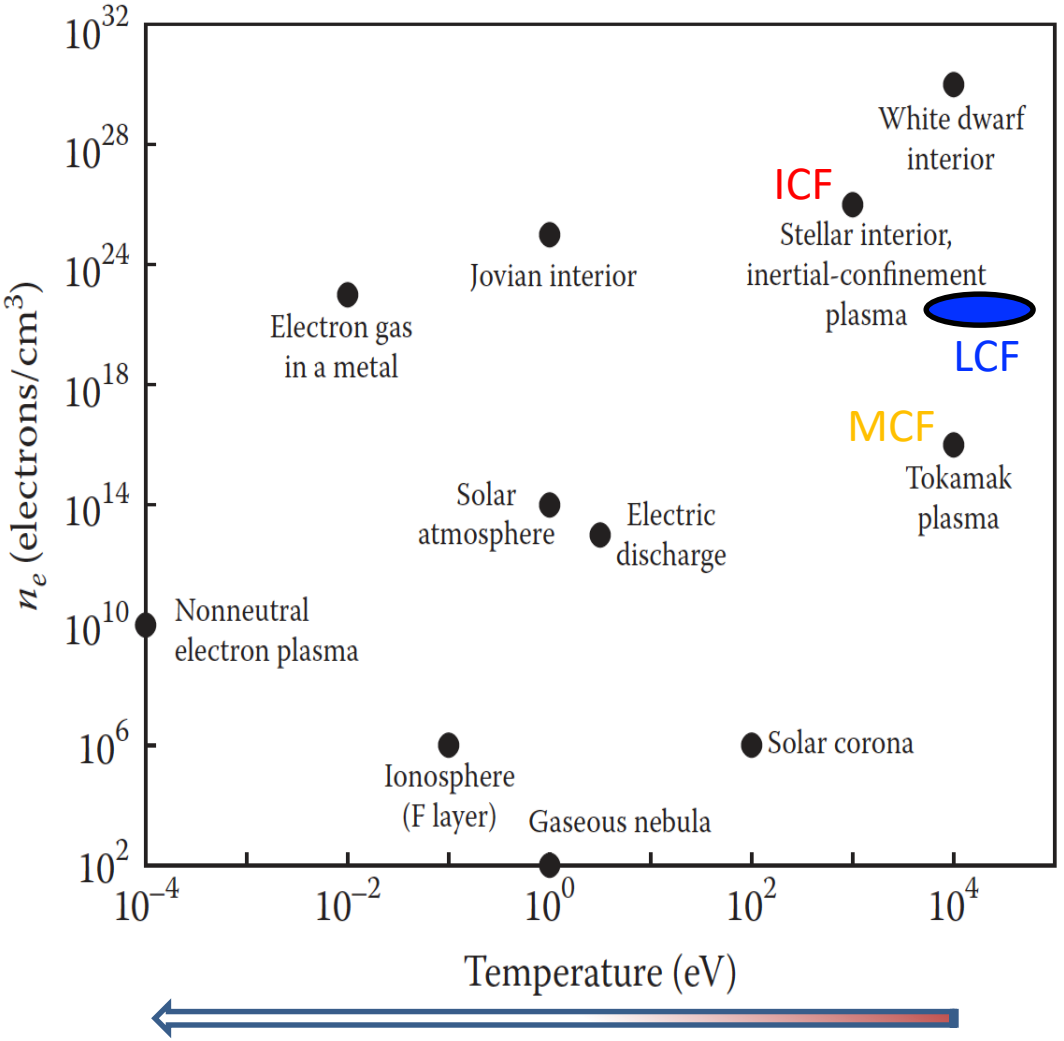
- Electron screening *shifts the Gamow Factor* as if deuterons were at far higher energies.
- This exponentially increases fusion rates.
- Laboratory astrophysics using accelerated deuteron beams across the Periodic Table show lattice and plasma screening provide up to 3+ keV screening.
- The *PRC* Theory Paper indicates a *higher probability of large angle scattering of screened charged particles* on screened deuterons.



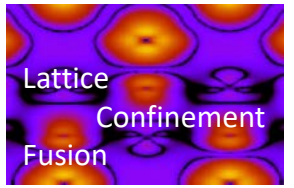
Electron Screened Enhanced Cross Sections

The Path: *Electron Screening [2]*

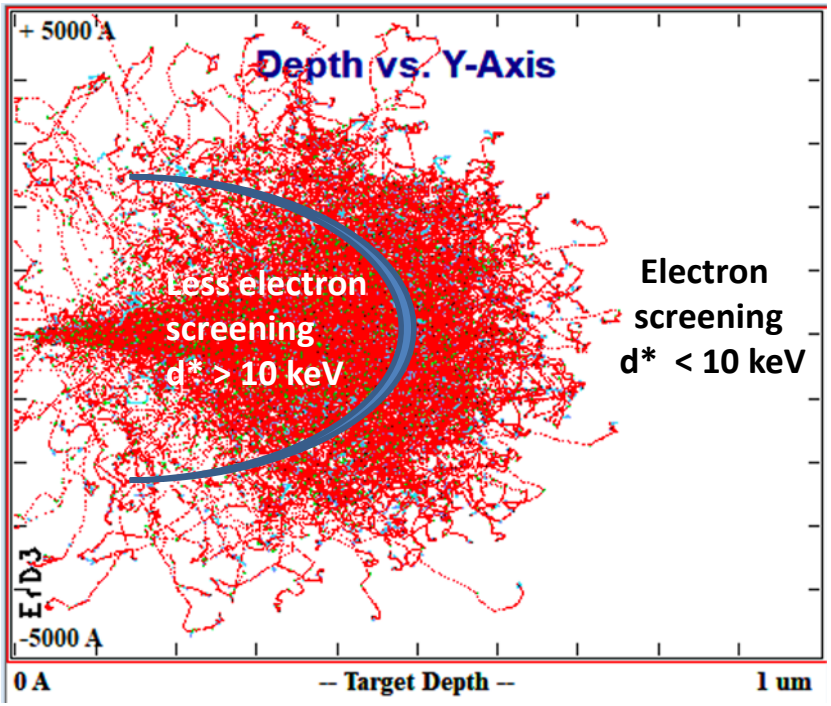
- Deuterated lattices have Fermi Degenerate electrons:
  - Metal conduction bands
  - Gas giant planets
  - White Dwarf Stars
- These effects are relatively temperature insensitive, relying upon densities > 10^{23} electrons/cm^3
- LBNL published results in *Nature* and the *Journal of Applied Physics* attribute a 100-fold increase in fusion rates to electron screening occurring at only 1.2 keV.
- *Screening is most effective < 10 keV.*



The Path: Electron Screening [3]



SRIM/TRIM Model of 64 keV d* Ion slowing in ErD_3 Lattice



10^3 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

Runs of 10^3 and 10^4 particles have identical trajectories.

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

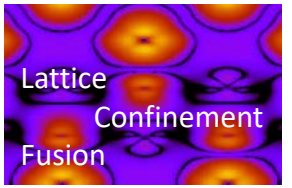
Free electrons increase plasma screening.

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

Initially, 20% of 64 keV d* will fall below 10 keV as it slows, but eventually all do.

Except when nuclear interactions occur.

The Path: *Comparing Fusion Methods [1]*

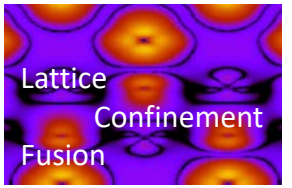


- ICF: Inertial Confinement Fusion *(e.g. laser fusion)*
- MCF: Magnetic Confinement Fusion *(e.g. tokamaks)*
- LCF: Lattice Confinement Fusion *(e.g. γ:TiD_2 and γ:ErD_3)*

Type	***Density*** (ions/cc)	***Ion$_T$*** (keV)	***Confinement Time***
ICF	10^{26}	3 - 10	nanoseconds
MCF	10^{14}	1 - 10	seconds
LCF	10^{23}	64 (Avg)	indefinite

- Lawson Criteria and Triple Product assume Ion$_T$ > 5 keV with the product of density x confinement time.
- *LCF averages Ion$_T$= 64 keV with indefinite confinement time.*

The Path: *Comparing Fusion Methods [2]*

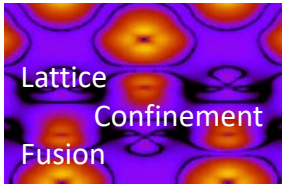


- Comparison
  - LCF uses bremsstrahlung γ as a *fusion match* rather than ICF lasers or MCF compressed plasma.
  - LCF uses fast neutrons and screened charged particles for efficient large angle scatter, momentum transfer while ICF and MCF rely upon inefficient small-angle scatter alpha heating.
  - Neutron mean-free Path (with confinement time and radii):

ICF	< 40 um	(nanoseconds, core diameter < 100 um)
MCF	10 km	(seconds, tokamak radius in meters)
LCF	1 cm	(indefinite time, lattice radii > 1 cm)

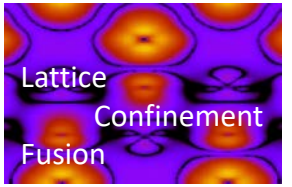
- *LCF benefits from both neutron and charged particle heating.*

Related Research



- Gunnersen, E. M. and James, G., "On the Efficiency of the Reaction H3(d,n)He4 in Titanium Tritide Bombarded with Deuterons", *Nucl. Inst. Methods*, **8**, 173-84 (1960) [AEC]
- Assenbaum, H.J., Langanke, K., and Rolfs, C., "Effects of Electron Screening on Low-Energy Fusion Cross Sections", *Z. Phys A – Atomic Nuclei*, **327,** 461-469 (1987). [Universität Münster]
- Hagino, K. and Balantekin, A.B., "Radiation correction to astrophysical fusion reactions and the electron screening problem", *Phys. Rev C.*, **66**, 055801 (2002). [U. of Wisconsin and Yukawa Institute]
- Bystritsky V.M. *et al*. "Measurements of Astrophysical S Factor and Screening Potential for d(d,n)^{3}He Reaction in ZrD_2, TiD_2, D_2O and CD_2 Targets in the Ultralow Energy Region Using Plasma Accelerators", *Nucl. Phys,* **75,** 156 (2012) [JINR, Dubna]
- "System and Method for Generating Particles", *US 8,419,919 B1* (2013) [JWK and US Navy]
- Wiśniewskia, R., Didyk A. Y. and T. Wilezinska-Kitowska, "Deuteron Disintegration, Thermonuclear and Nuclear Fission Reactions Induced by γ Quanta in D-Saturated Palladium and Dense Deuterium Gas with Synthesis of New Structures" *J. of Surface Investigation, Synchrotron and Neutron Techniques*, **7**(2) 239-247 (2013). [JINR, Dubna]
- Schenkel, T. *et al*., "Investigation of light ion fusion reactions with plasma discharges", *J. Appl. Phys*., **126**, 203302 (2019). [Lawrence Berkeley National Laboratory]
- Fork, D., *et al*., "Enhanced Electron Screening Through Plasmon Oscillations", *US 2019/0043624 A1* (2019) [Google and U. of Maryland]
- "Advanced Energy and Propulsion Research and Development", *NCRADA*, (2020) [JWK and US Navy]
- "10th European Summer School on Experimental Nuclear Astrophysics", *EPJ Web Conf*, **227** (2020)

In Conclusion



- Modeling allows us to predict the best lattice materials, mass, geometry and reaction rates
- There is a "sweet spot" between neutron heating in a confined lattice and locally warm dense matter driven by electron screening.
- Subsequent work will explore neutron heating, screened charged particle scattering, and scaling while searching for the sweet spot.
- Besides energy research, LCF provides means to explore electron screened, warm dense matter, laboratory astrophysics.
- *There are many ways to skin a cat once you know there's a cat!**

**(no cats were harmed in this research)*



Questions?

I/O Tool

https://arc.cnf.io/sessions/z7mg/#!/dashboard

LCF Workshop: Wrap-up

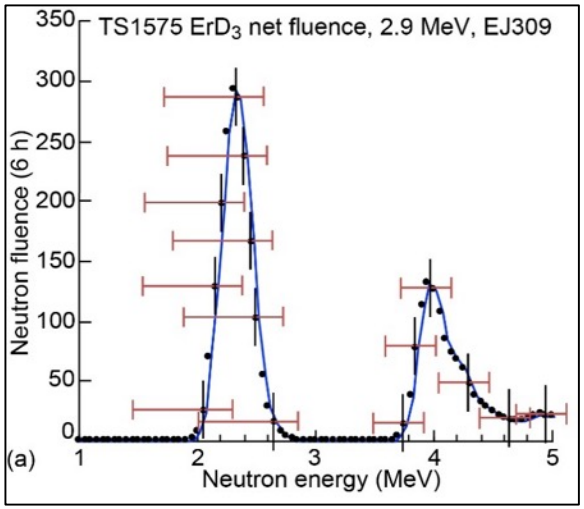
Dr. Theresa Benyo
Analytical Physicist, Materials & Structures Division
NASA GRC

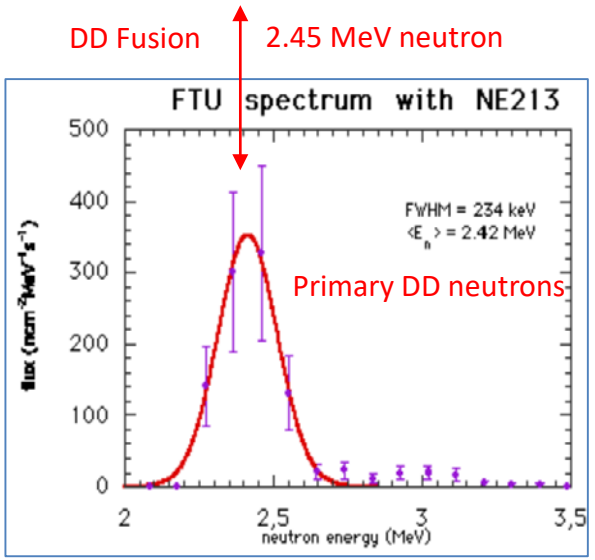


NASA Glenn Research Center
Advanced Energy Conversion Team
May 21, 2020

LCF Workshop Wrap-up

- Thank you to the speakers, panelists and participants
- Evidence of novel nuclear reactions
  - Neutron spectroscopy showed evidence of fusion neutrons at 2.45MeV and boosted fusion neutrons at 4 & 5 MeV

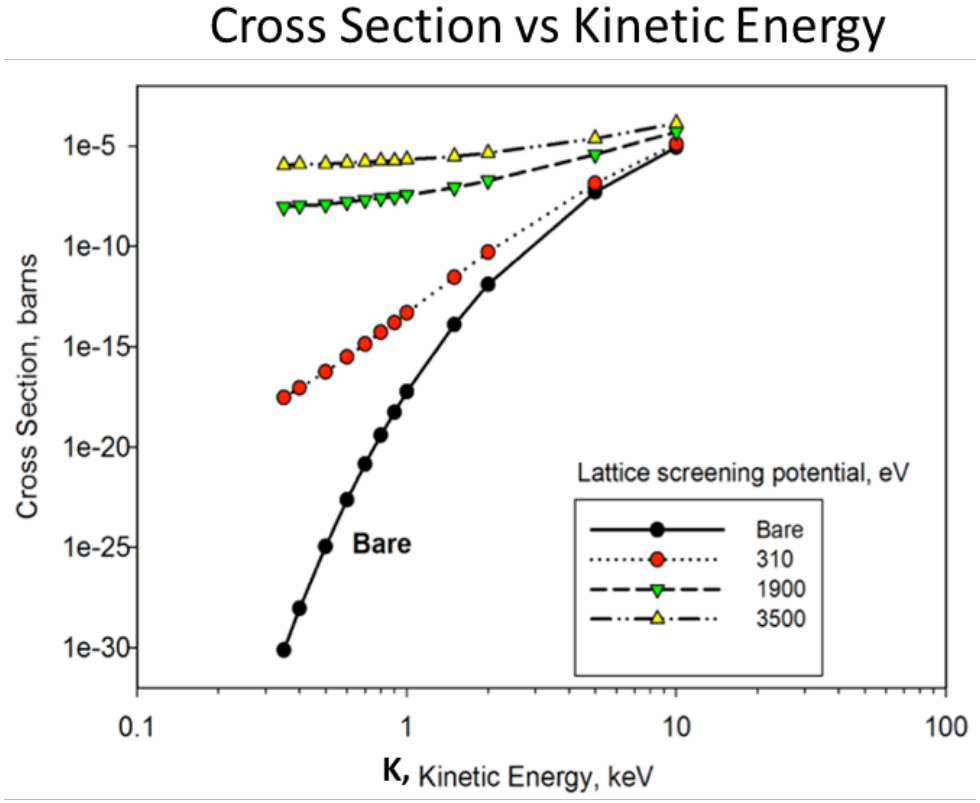




Italian ENEA Tokamak

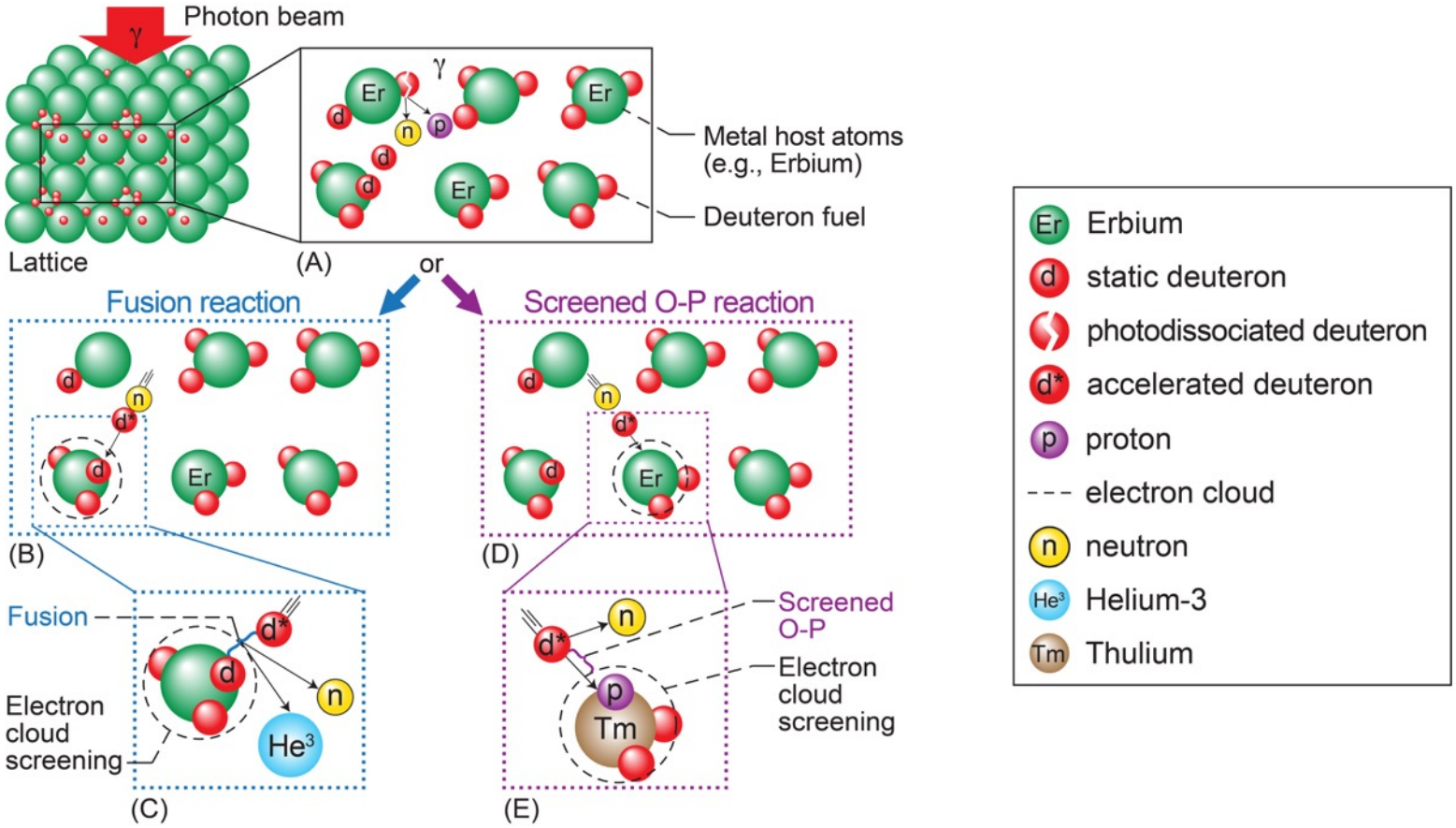
LCF Workshop Wrap-up

- Theory behind the novel nuclear reactions
  - Electron screening in a confined lattice which allows enhanced nuclear fusion



LCF Workshop Wrap-up

- AEC Team discovers lattice confinement fusion



LCF Workshop Wrap-up

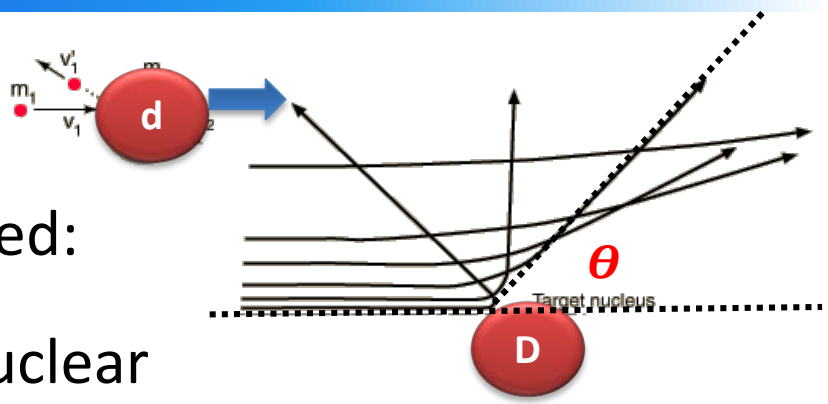
- Acknowledgements:
  - Megan Sigetic – LCF Animation
  - Laura Alford – LCF Invitation List
  - Laura Becker & Lorie Passe – Publication Editing
  - Vadim Lvovich – Workshop Preparation/Feedback
  - Larry Forsley – Workshop Organization
  - Matt Forsbacka, Mike Houts, Ron Litchford, and John Scott – LCF panelists
  - Workshop Participants!
- Thank you for your participation!!



Appendix

Why Significant?

- Unique environment for fusion
  - Globally “cold” locally “hot”
- D-D interactions are highly screened: **most favorable large/small angle scattering probability** = highest nuclear tunneling probability
- Bremsstrahlung photo neutrons used to heat d to cause d-D fusion
  - Localized fusion rates enhanced by efficient electron screening in a dense fuel environment (~10^{23} fuel atoms/cm^3)
  - Other neutron source may be substituted for photo-neutrons
- Window into novel path of initiating d-D fusion



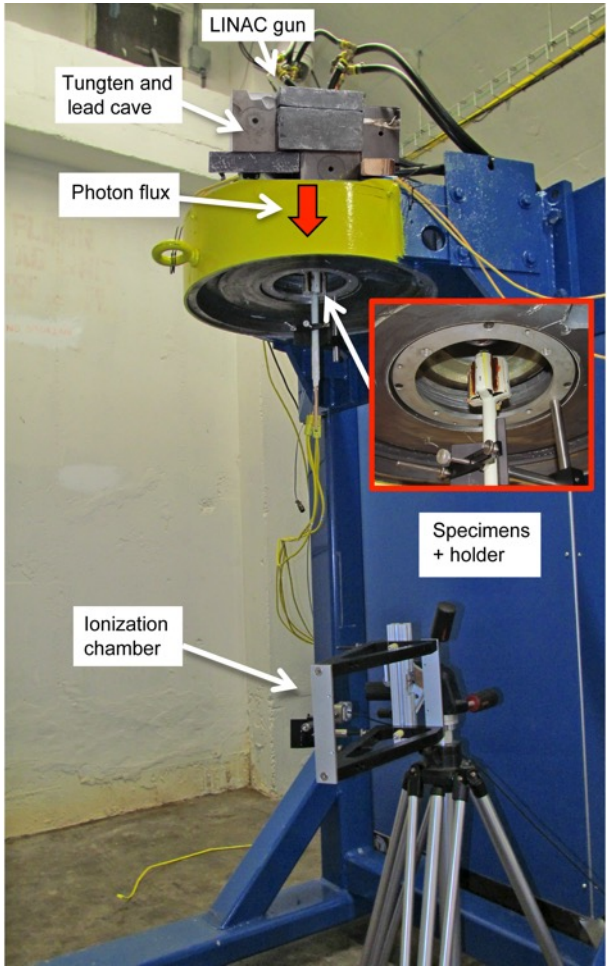


Appendix

Experimental Paper

Motivation for Work at IBA

- Tests performed with 1.95 MeV LINAC beam at Plum Brook (circa ‘15-’16) resulted in deuterated specimens to ”activate” at photon energies below deuterium photo dissociation (2.226 MeV)
  - HPGe Gamma signatures showed activation
  - CR-39 solid state neutron detectors showed evidence of MeV to >10MeV neutron emissions when no neutrons should have been present
  - Above evidence suggests a subthreshold mechanism has been found to cause fusion reactions
- Though GRC used accepted techniques for measuring beam energy, there is a small chance that some electrons hitting the braking target could have been above deuterium photo dissociation energy
- IBA Industrial offers a Dynamitron beam whose electron energy can be easily measured and controlled to ~1-2% of set point. Utilized IBA Beam to:
  - Evaluate if specimen activation can be repeated with a well-calibrated beam
  - Utilize improved neutron diagnostics to measure/record activity during the test to allow better understanding of the physical mechanism(s) at work



LINAC 2:
1.95 MeV; 176 uA

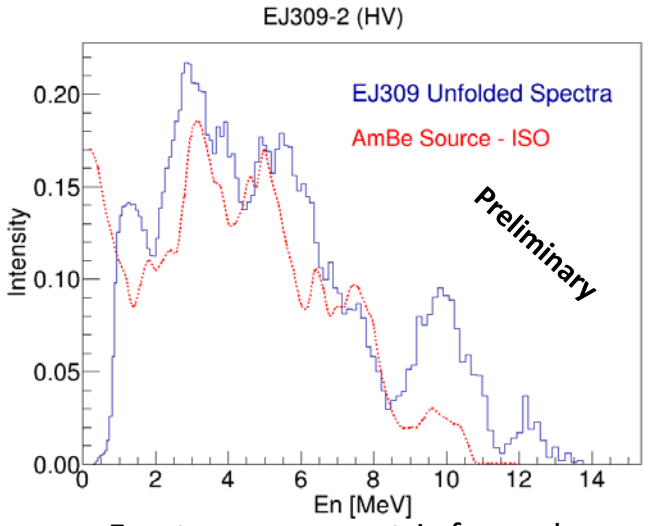
Prompt Neutron Detection Calibration Approach

Calibrate with accepted calibration standards for electron energy equivalents gamma: Cs-137, Co-60

Utilize MCNP, PoliMi to create detector response functions

Utilize HEPROW to unfold detector response → neutron counts and energies at detector for the following:
Calibration standards: e.g. AmBe
Experimental neutron spectrum

PSD: Unfolded Spectra (AmBe)

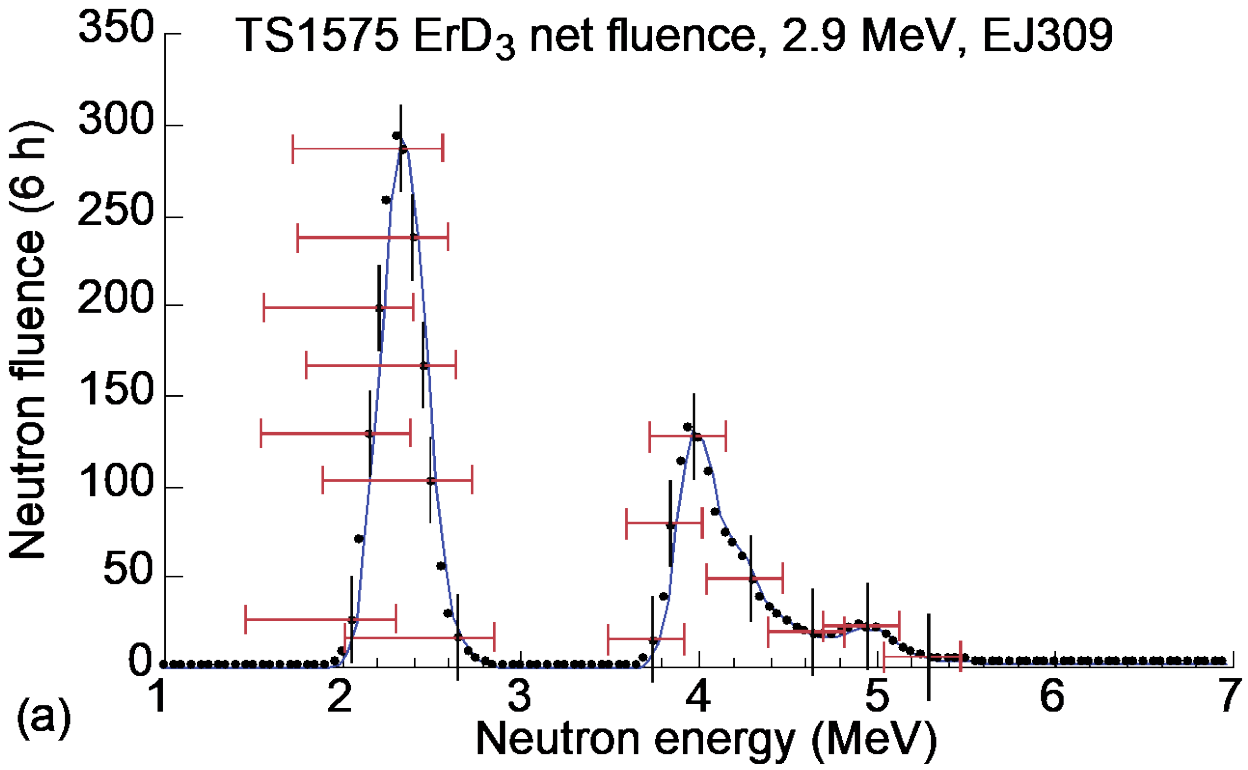


Exact response matrix for each detector in process

Limits of Detection (neutron energies)

- Scintillators:
  - EJ309: >500 keV to 14 MeV
  - Stilbene: > 300 keV to 14 MeV

Measurement Uncertainty



Horizontal Uncertainty Bands: ±3σ

- Determined by perturbation method;
- Examined the response of the detectors to established γ-ray peaks for standard check sources (^{137}Cs and ^{60}Co) and fitted Gaussian distribution netting 1σ ±50 keVee →3σ = ±150 keVee
- Re-ran unfolding algorithm using perturbed energy inputs to result in perturbed neutron energies

Vertical Uncertainty Bands: ±3σ

- Vertical fluence uncertainty determined by using standard deviation (σ) in GRAVELW unfolding methodology
- Re-ran unfolding algorithm at +3σ and then -3σ to obtain fluence uncertainty bands plotted

Conventional Hot Fusion vs. Screened Process

$$R \sim n_1 n_2 \sigma v$$

To increase R:

- Increase density of reactants ($n_1 n_2$)
- Increase reaction cross-section (σ)

Reaction Rate (#/sec/cm^3)	=	Large angle scattering probability	x	Nuclear tunneling probability	x	Fuel n1 (#/cm^3)	x	Fuel n2 (#/cm^3)
Conventional hot fusion		Very Low		Low (keV)		Fuel Hot Low (10^16/cm^3)		Fuel Hot Low (10^16/cm^3)
Screened fusion process		High		High (keV-MeV)		Fuel Hot Very Low (10^10/cm^3)		Fuel Cold Very High (10^22/cm^3)

Appendix

Publications

Conference Papers, NASA TMs, Presentations and Patent Applications

- Benyo, T.L. *et al*., "Investigation of Deuterium Loaded Materials Subject to X-ray Exposure", *NASA TM-2015-218491/REV1*, (2015)
- Pines, V., *et al*., "METHODS AND APPARATUS FOR ENHANCED NUCLEAR REACTIONS", *USPTO Application 20170263337* (2016)
- Steinetz, B., *et al*., "Experimental Observations of Nuclear Activity in Deuterated Materials Subjected to a Low-Energy Photon Beam", *NASA TM-2017- 218963*, (2017).
- Forsley, L., "Space Power: The Genie Fast-Fission Sub-Critical Core", *ANS, Nuclear and Emerging Tech. for Space*, Las Vegas, NV (2018).
- Benyo, T.L., *et al*, "Evidence of Electron-screened Oppenheimer-Phillips Reactions ^{162}Er(d,n)^{163}Tm or ^{162}Er(p,γ)^{163}Tm in Deuterated Materials Subjected to a Low-energy Photon Beam", *9th Int. Particle Accelerator Conference*, Vancouver, Canada, (2018).
- Benyo, T.L. *et al*., "Gamma Energy Evaluation for Creation of ^{111m}Cd, ^{113m}In, and ^{115m}In Isotopes", *European Nuclear Physics Conference*, Bologna, Italy, (2018). (refereed publication)
- Forsley, *et al*., "Cryogenically Stable Propellant", NASA Patent Disclosure 1568407350. (2019).

Journal Papers, NASA TMs and Patents in Process

- Fralick, G., *et al*., "Transmutations Observed from Pressure Cycling Palladium Silver Metals with Deuterium Gas", *TBD* (2020).
  - Final revisions in process; To be submitted to *International Journal of Hydrogen Energy*
- Baramsai, B., *et al*., "Fast Neutron Spectroscopy with Organic Scintillation Detectors in High Radiation Environments", *TBD* (2020).
  - Submitted to *Nuclear Instruments and Methods (NIM) in Physics Research Part A* journal; in revision stage
- Ugorowski, P., *et al*., "Fast Neutron Spectroscopy with a Volumetrically-Sensitive, Moderating-Type Neutron Spectrometer in a High Radiation Environment", *TBD* (2020).
  - Final revisions in process; To be submitted to the *NIM in Physics Research Part A* journal
- Smith, P., *et al*., "Bubble Detector Neutron Dosimeter Measurements During Electrolytic Co-Deposition", *TBD* (2020).
  - In review
- DeChiaro, L.F., "A Summary of Density Functional Theory Calculations in Selected Binary and Ternary Metal Alloys and Hydrides", *TBD* (2020).
  - Joint Navy/NASA Technical Report
- DeChiaro, L.F., *et al*., "A Multi-Laboratory Study of Anomalous Elements and Magnetic Field Orientation Effects in LENR Codeposition Experiments", *TBD* (2020).
  - Joint NAVY/NASA Technical Report
- DeChiaro, L. F., *et al*., "Method for Improving Nuclear Reactions by Modified Magnetic Fields", *TBD* (2020).
  - Patent to be filed