Briefing on Low-Energy Nuclear Reactions (LENR) Research

A scientific survey of the international literature in response to the FY16 NDAA (report on HR4909, 4 May 2016)

Office of the ASD(R&E) / Research

House Committee on Armed Services Briefing Request

The committee is aware of recent positive developments in developing low-energy nuclear reactions (LENR), which produce ultra-clean, low-cost renewable energy that have strong national security implications. For example, according to the Defense Intelligence Agency (DIA), if LENR works it will be a "disruptive technology that could revolutionize energy production and storage." The committee is also aware of the Defense Advanced Research Project Agency's (DARPA) findings that other countries including China and India are moving forward with LENR programs of their own and that Japan has actually created its own investment fund to promote such technology. DIA has also assessed that Japan and Italy are leaders in the field and that Russia, China, Israel, and India are now devoting significant resources to LENR development. To better understand the national security implications of these developments, the committee directs the Secretary of Defense to provide a briefing on the military utility of recent U.S. industrial base LENR advancements to the House Committee on Armed Services by September 22, 2016. This briefing should examine the current state of research in the United States, how that compares to work being done internationally, and an assessment of the type of military applications where this technology could potentially be useful.

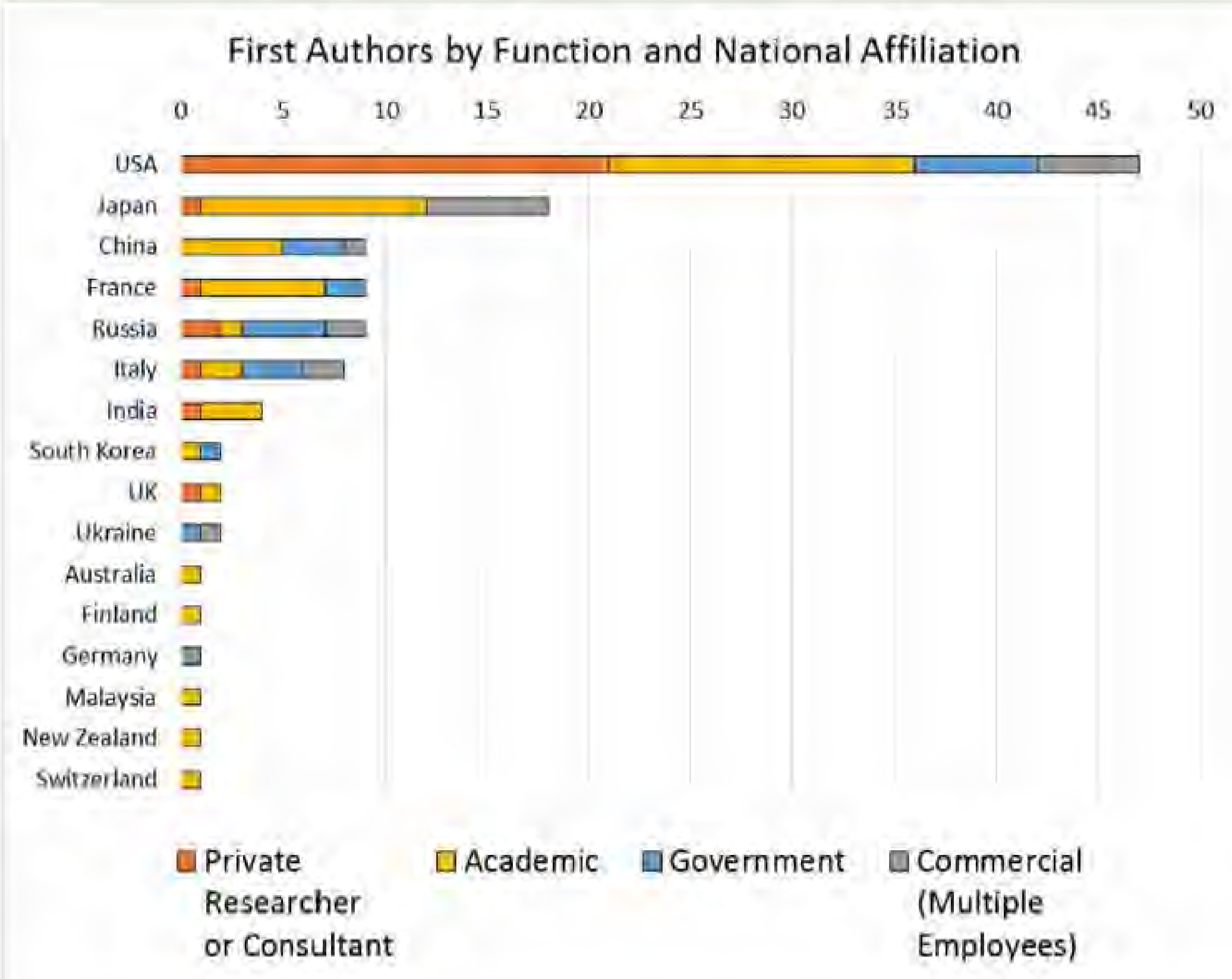
Preparation of this Briefing

- The Naval Research Laboratory (NRL) was tasked by OSD to conduct a comprehensive survey on the current state of research on low-energy nuclear reaction (LENR) in the US, and an assessment of the type of military applications for this technology.
- A comprehensive collection and analysis of international literature on LENR since 2004 (the last Department of Energy review) was conducted.

Low-Energy Nuclear Reaction (LENR) executive summary

- The United States is active in LENR research in universities, government labs, industry and private research
- The status of knowledge, evidence, and technology indicates that it is premature to increase investments in LENR research
- LENR research has been challenged by a lack of reproducibility of results, and many of the studies have not provided the necessary scientific and theoretical foundations
- Beyond the lack of reproducible positive results to date, scaling to meaningful energy production levels must still be addressed.
- If LENR research can successfully provide a reliable energy source, and the underlying science can be established, it could lead to a broad variety of military as well as commercial applications such as a compact, efficient, room temperature energy source.

U.S. is Well Represented in LENR



Technology Readiness Level (TRL) assessment for Energy production

Production	TRL 9
Full scale development	TRL 8
	TRL 7
Exploratory development	TRL 6
	TRL 5
	TRL 4
	TRL 3
Technology development	TRL 2
	TRL 1

LENR research:

- **Most results have not been reproduced independently;**
- **Lack scientific and theoretical foundations.**

LENR proponents claim many potential military applications

If LENR research can successfully provide a reliable energy source, and the science can be established, the following could result:

- Abundant, clean energy
- Compact, portable power source
- Inert and nonhazardous
- Processing of radioactive waste

Energy Density of Fuels

Mosier-Boss *et al.* Final Report 2016

http://fusionforenergy.europa.eu/understandingfusion/merits.aspx

Nuclear Physics and LENR

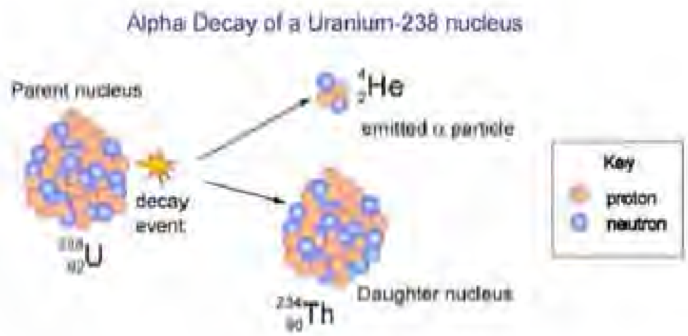
- **Physics of Nuclear Reactions**
- **Physical challenges for Nuclear Fusion**
- **Two LENR research areas:**
  - Muon-Catalyzed Fusion: Broadly accepted, based on well understood physics
  - Electrolytic Cell: Has not been reproduced independently and has not provided the necessary technical information to provide a scientific foundation for scalable research.

Physics of Nuclear Reactions

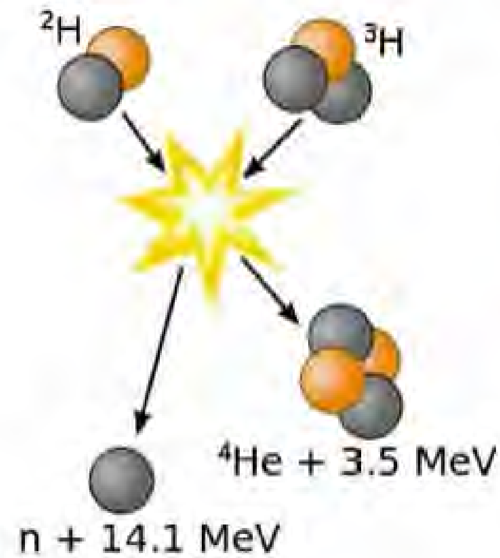
- **Definition:** a process in which two nuclei, or a nucleus of an atom and a subatomic particle (such as a proton, neutron, or high energy electron) from outside the atom, collide to produce one or more nuclides.
- A nuclear reaction must cause a transformation of at least one nuclide to another.
- In 1917, Ernest Rutherford demonstrated transmutation of nitrogen into oxygen at the University of Manchester. This was the first observation of an induced nuclear reaction, that is, a reaction in which particles from one decay are used to transform another atomic nucleus.
- The modern nuclear fission reaction was discovered in 1938 by the German scientists Otto Hahn and Fritz Straßmann.

Types of Nuclear Reactions

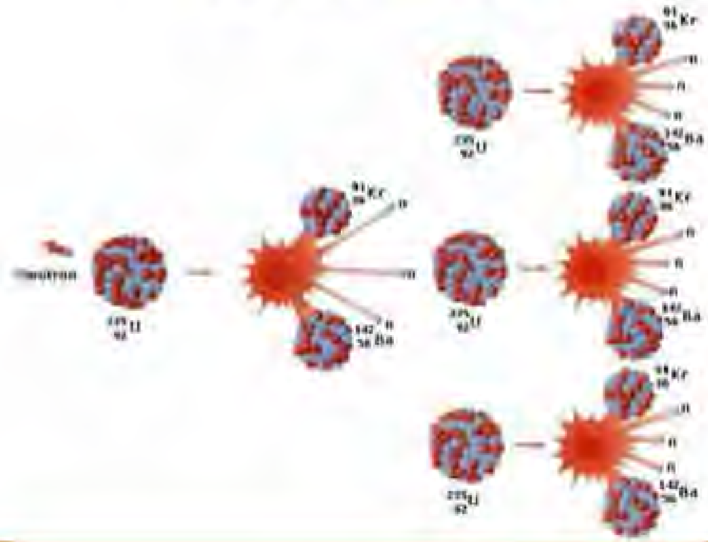
Nuclear decay



Nuclear fusion



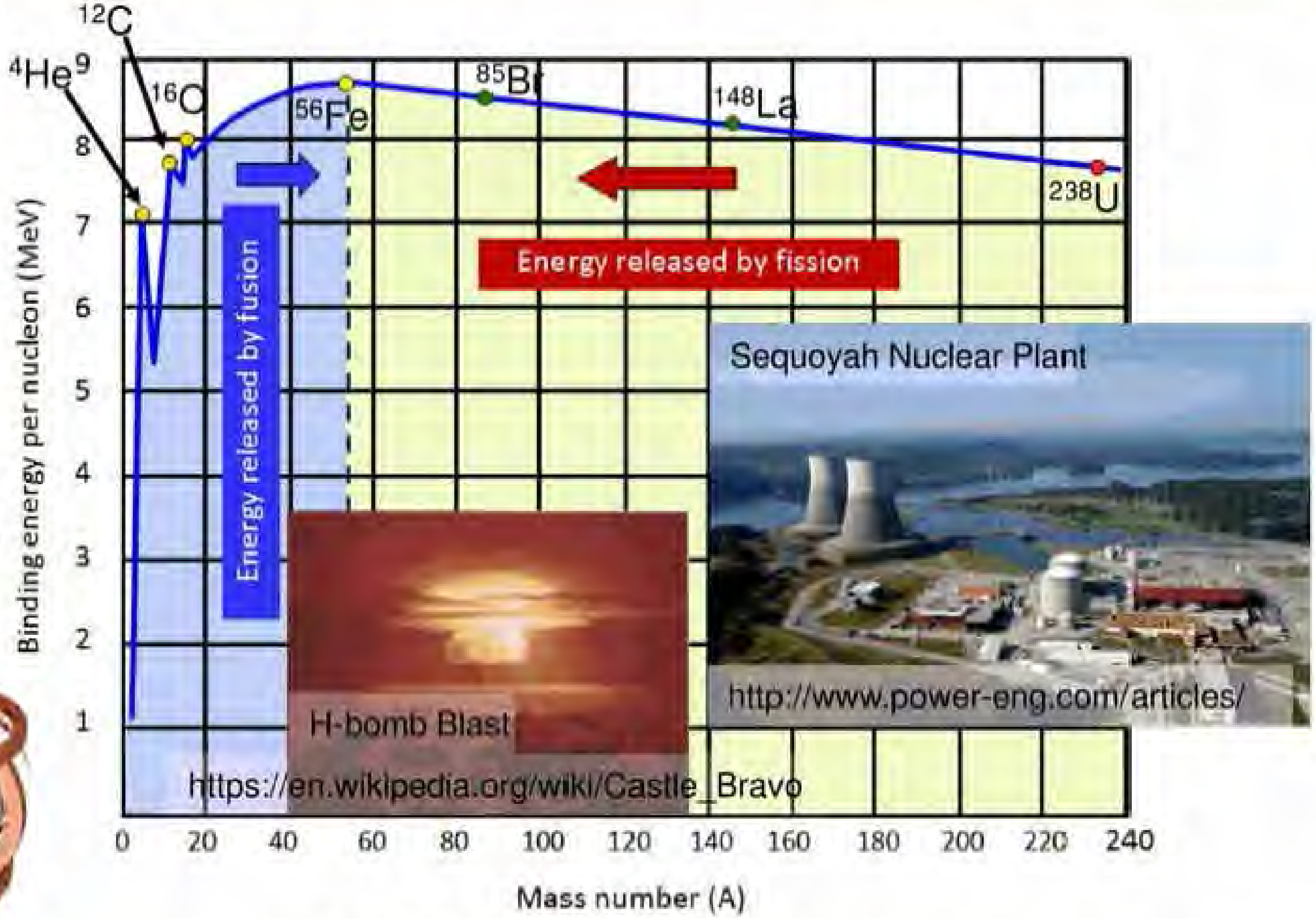
Nuclear fission



Energy production: Fission vs. Fusion

Sun Powered by Nuclear Fusion

http://sdo.gsfc.nasa.gov/gallery/main/



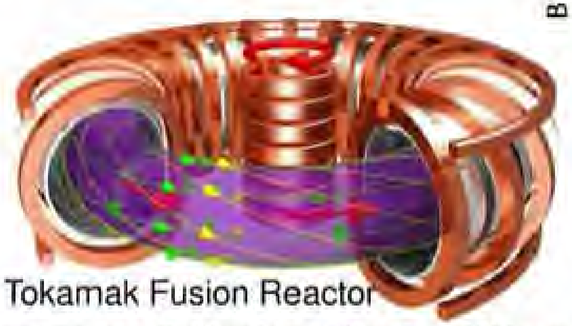
H-bomb Blast

https://en.wikipedia.org/wiki/Castle_Bravo

Sequoyah Nuclear Plant

http://www.power-eng.com/articles/

http://www.schoolphysics.co.uk/



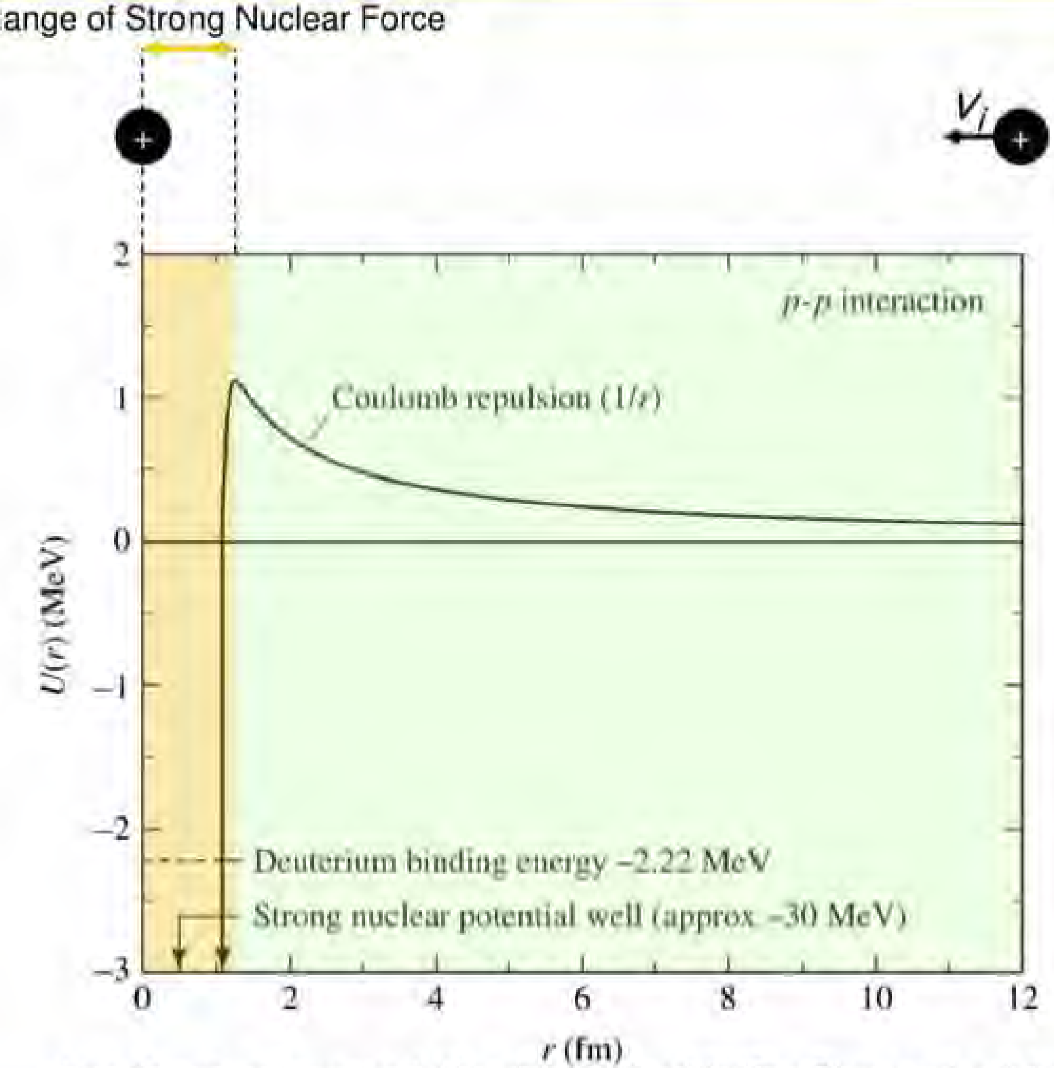
Tokamak Fusion Reactor

Image credit Matthias Hirsch / Wikimedia

Slope of Binding Energy curve demonstrates fusion reactions are more energy dense than fission reactions.

Challenge for Nuclear Fusion:

Squeeze two positive charges together (against the Coulomb repulsion)

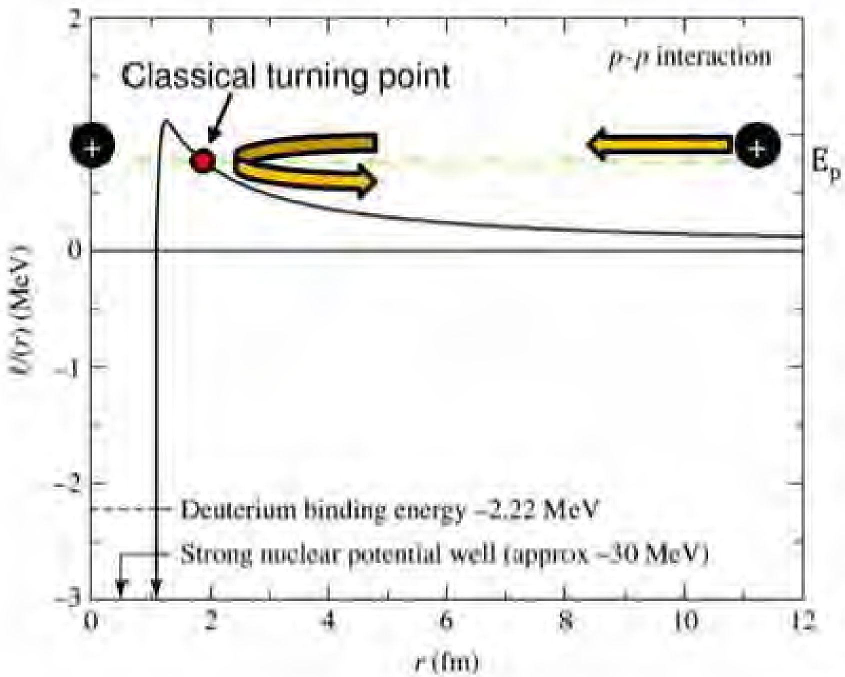


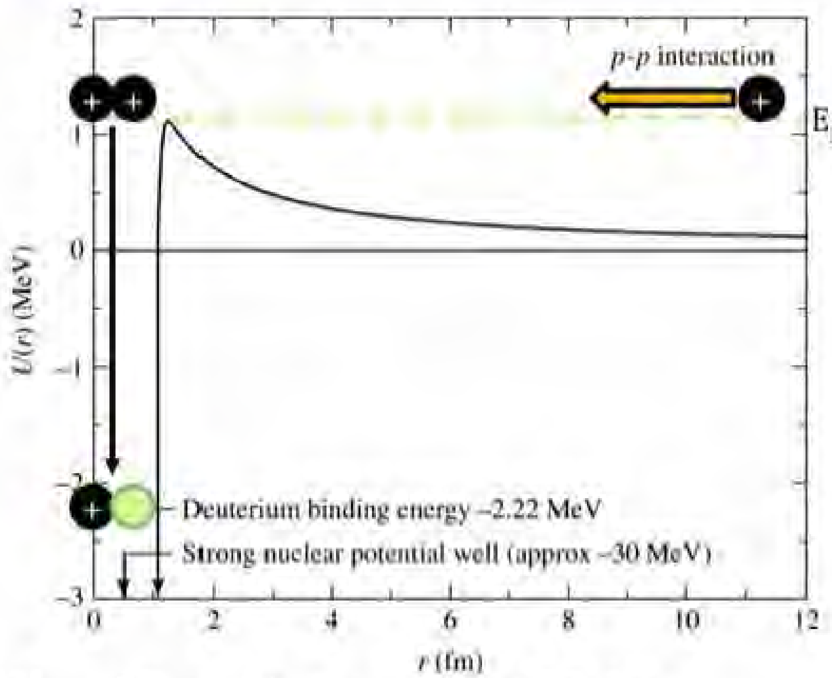
http://burro.astr.cwru.edu/Academics/Astr221/StarPhys/coulomb.html

Reactants must approach within ~ 10^{-15} m for strong nuclear force to act.

Energy Required for Fusion

Classical mechanics requires particle energy to be greater than the Coulomb potential.

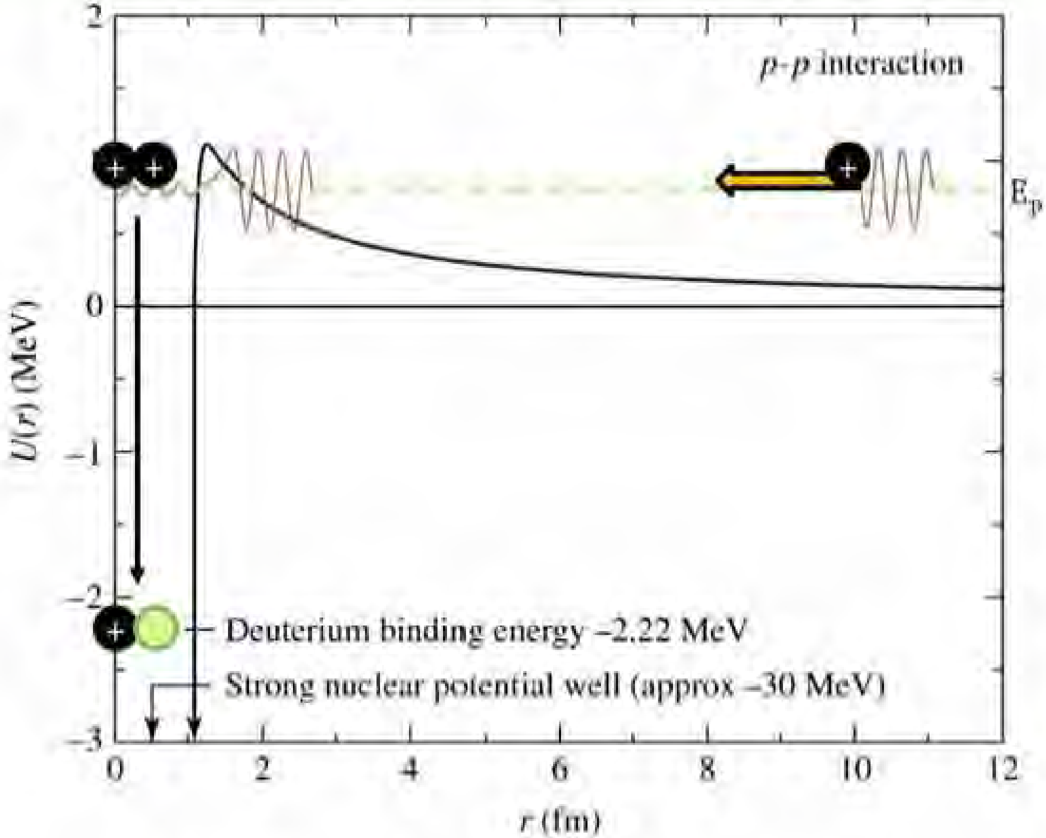




$$^1_1\mathrm{H} + {}^1_1\mathrm{H} \rightarrow {}^2_1\mathrm{D} + e^+ + \nu + 0.42\ \mathrm{MeV}$$

Converting 1 MeV to temperature → ~10^{10} °C. Sun's core temperature ~10^7 °C

Quantum Mechanical Tunneling is Essential for Fusion



$$ {}_1^1\mathrm{H} + {}_1^1\mathrm{H} \rightarrow {}_1^2\mathrm{D} + \mathrm{e}^+ + \nu + 0.42\ \mathrm{MeV} $$

Tunneling Probability

$$ \ln P = -\frac{\pi k q_1 q_2}{\hbar}\sqrt{\frac{2m}{E}} $$

$$ P \sim 0.001\ @\ 10\ \mathrm{keV} $$

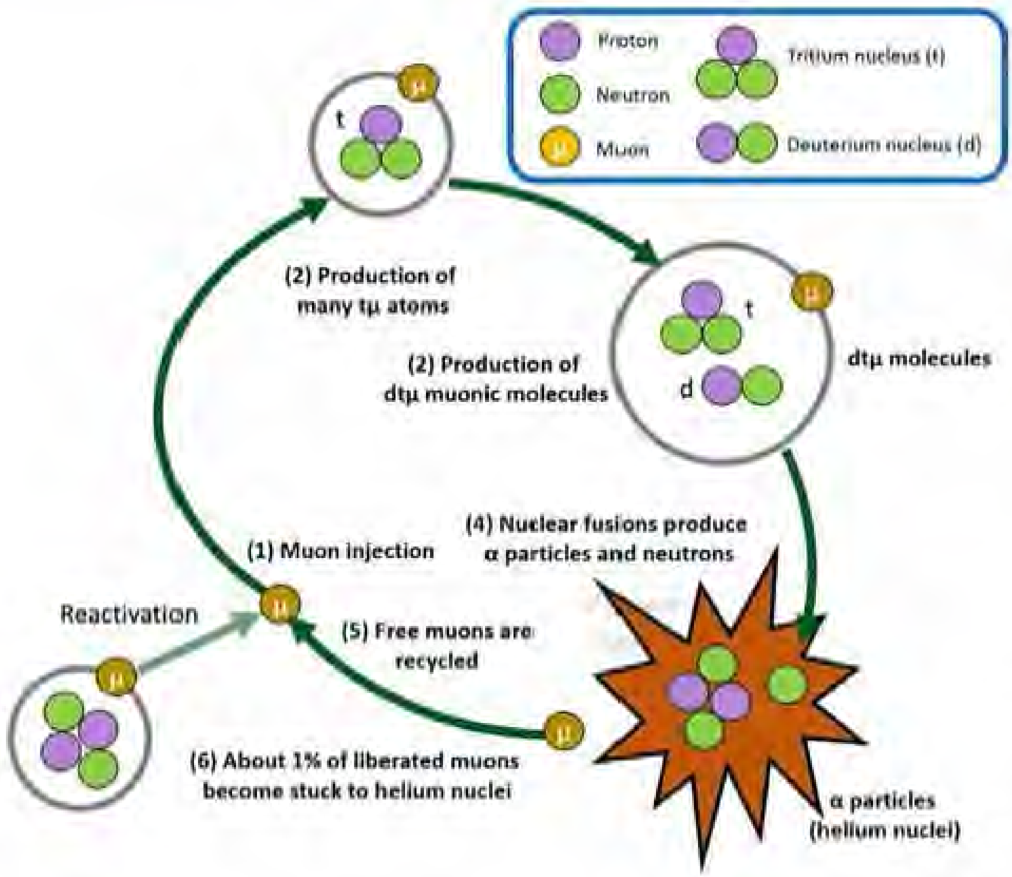
$$ P \sim 1 \times 10^{-1921}\ @\ \mathrm{Room\ Temp} $$

Odds of winning the Powerball Jackpot

$$ P \sim 3 \times 10^{-10} $$

Tunneling is not enough, one solution is to add heat.

Muon-Catalyzed Fusion (MCF): Uncontroversial and Well Understood



http://large.stanford.edu/courses/2016/ph241/yoon1/

- Muon – similar to electron, ~200× more massive
- Muon replaces an electron in molecular hydrogen
- Yields ~200× smaller bond separation ~3.5×10^{-13} m
- Increased tunneling probability leads to spontaneous fusion
- In general, muon is free to catalyze more reactions
- Sticking Probability – probability that muon remains bound to product and cannot catalyze more reactions before decaying

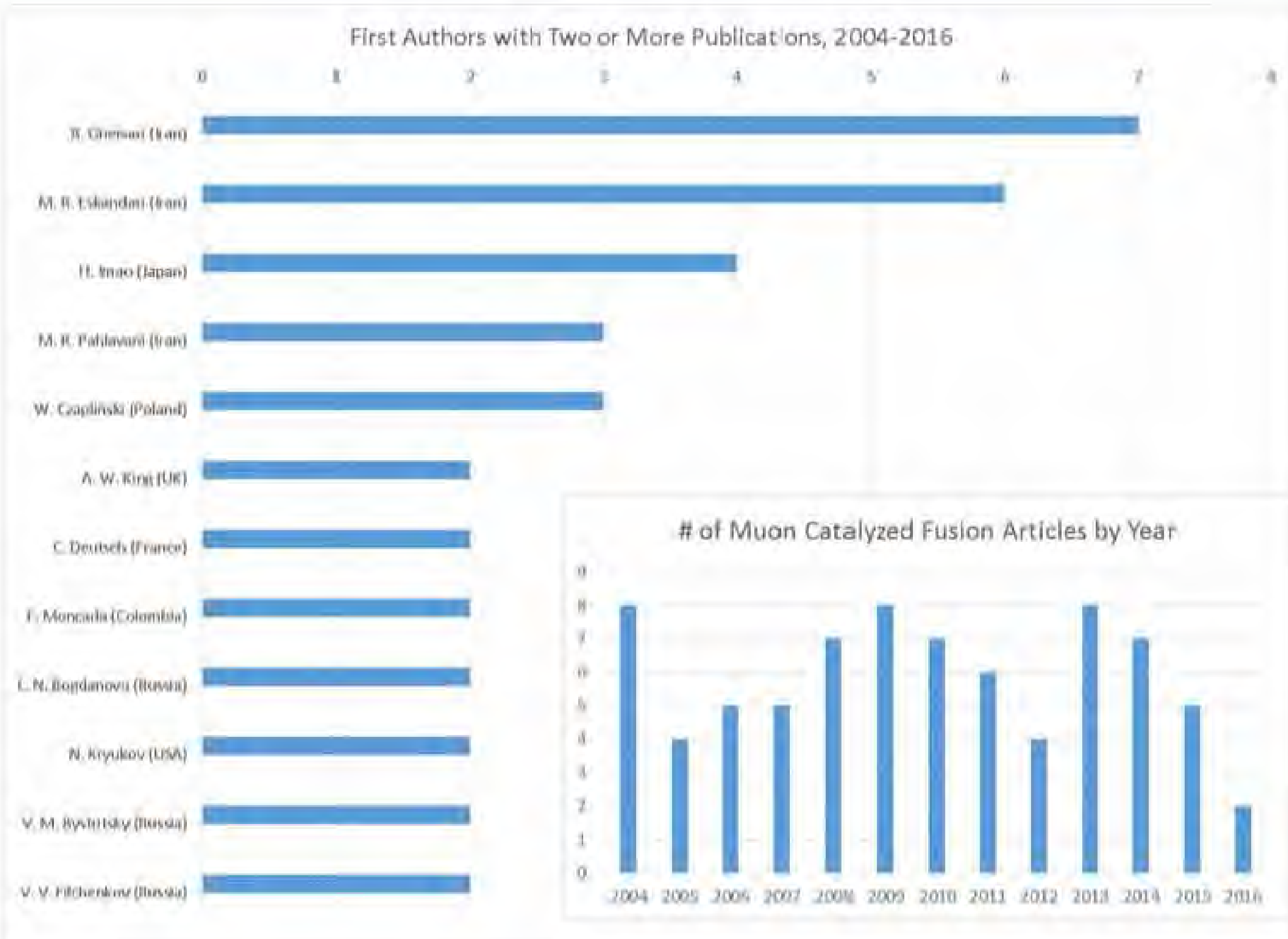
MCF: Impractical for Energy Production

- State of art: 1 Muon catalyzed ~150 fusion reactions (S. Jones et al. Brigham Young University, 1986).
- ~10 GeV required to produce 1 Muon.
- 1 Muon produces at most ~2.7 GeV (< 10 GeV).
- 1 Muon must catalyze 8000-11000 reactions to break even.

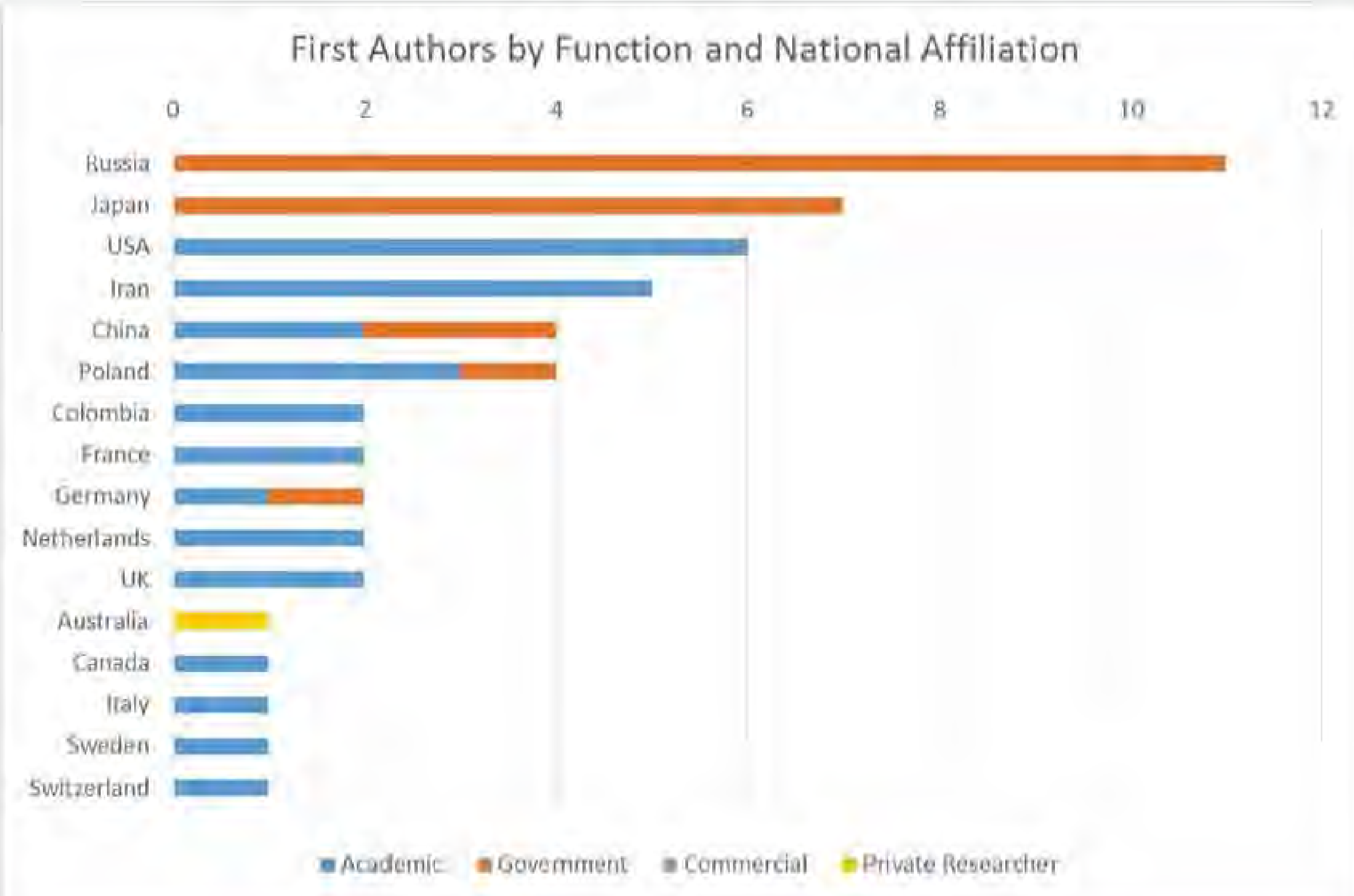
MCF: current research directions

- **Detailed calculations of wave functions for muonic molecule formation and muonic molecule bound state**
- **Detailed calculations of MCF parameters**
- **Approaches of increasing muon production efficiency**
  - Using pions from ICF to catalyze fusion reactions to increase overall efficiency
  - MCF in dense, hot plasmas, which reduces muon sticking.

Publications on MCF

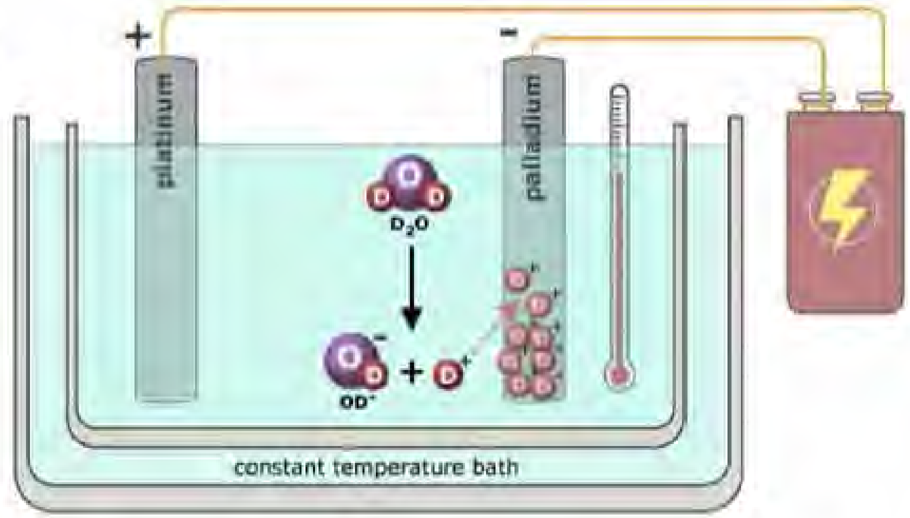


Nations for MCF research



Electrolytic Cell: Early Experiments

- In 1989, Pons and Fleischmann claimed to have observed excess heat from an experiment involving the electrolysis of heavy water using a palladium electrode
- Numerous attempts failed to replicate these results
- No nuclear products were observed along with the excess heat
- Measurement errors in calorimetry may have contributed to observation of excess heat.
- Also in 1989, S. Jones of Brigham Young University using similar electrolytic cells observed neutrons, but no excess heat.

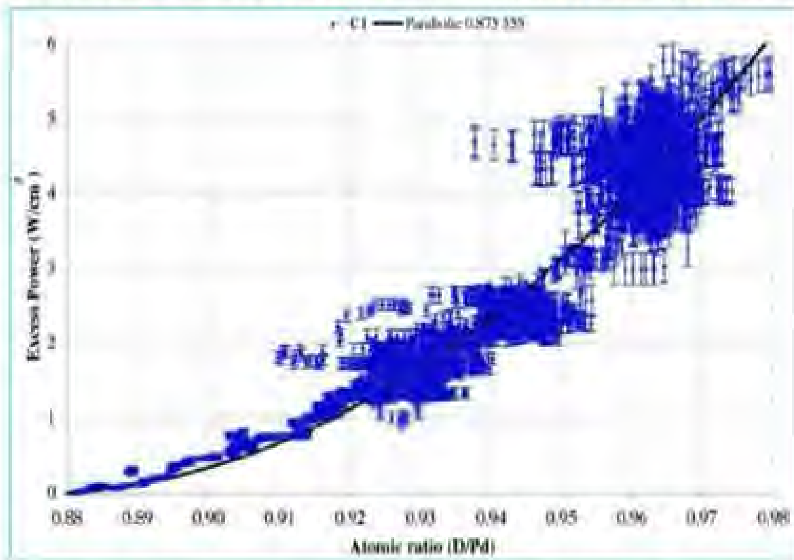


http://undsci.berkeley.edu/article/0_0_0/cold_fusion_03

Early Electrolysis Experiments Using Heavy Water Were Discredited

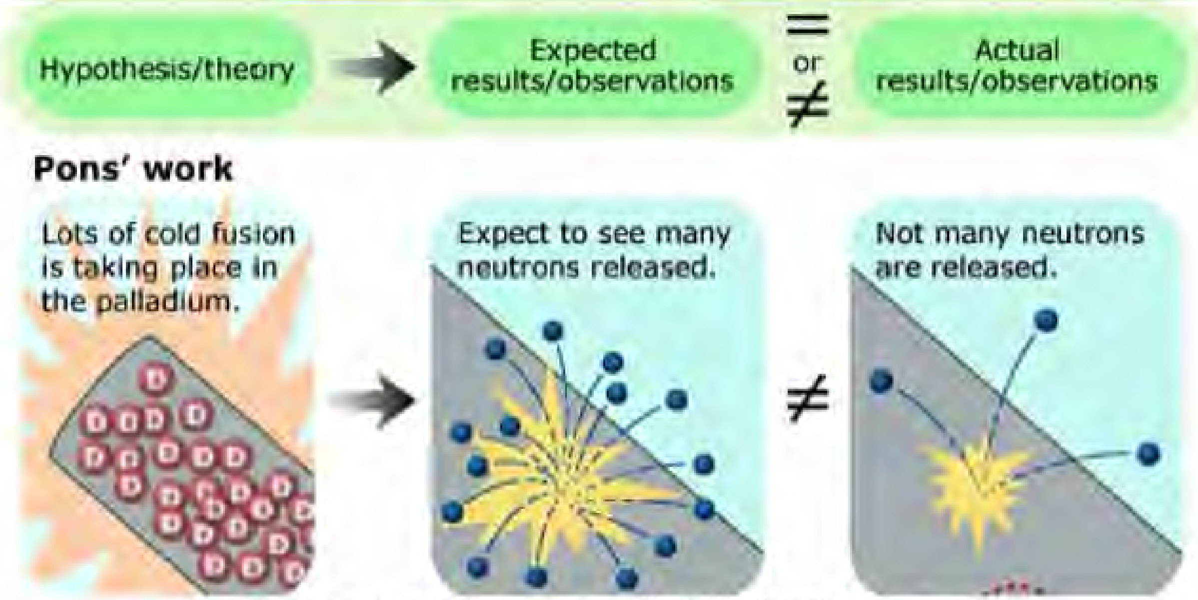
- 2004 Review of LENR research by Hagelstein *et al.* claimed Helium production correlated with excess heat measurements
- Review evaluated by Department of Energy in 2004, which recommended experiments to search for fusion events in thin deuterated foils, but not focused federally funded program for LENR.
- Sufficient deuterium loading required for excessive heat, suggested as reason for early negative results [McKubre Proceedings of ICCF 2009]
- Even with large deuterium loading, negative results still observed [McKubre Proceedings of ICCF 2009]

Reported Excess Heat vs Deuterium Loading Ratio



Hagelstein *et al.* 2004 DOE Report

Lack Theoretical Foundation



http://undsci.berkeley.edu/article/0_0_0/cold_fusion_03

- Spin-Boson Oscillator Theory[1] – the energy released in deuterium- deuterium fusion goes into large numbers of low energy phonons that heats the system
- Hydroton Theory[2] – formation of nuclear active environments in nano cracks resulting from electrolysis or gas loading

Predicts excess heat should be 23.8 MeV/He atom, which is not observed in experiments

[1]Hagelstein and Chaudhary Proceedings ICCF-14 (2008)
[2]Storms J. Condensed Matter Nucl. Sci. (2012)

- Cluster Fusion Theory – seeks to investigate multibody fusion for enhanced fusion rates. Four deuterons arranged in a tetrahedral symmetric configuration yielding 4 He atoms.

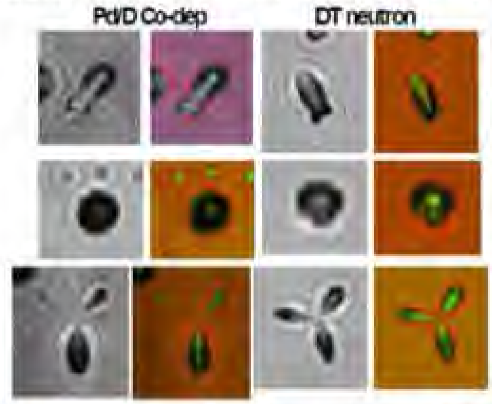
No mechanism given to produce tetrahedral symmetric configuration

Takahashi *J. Condensed Matter Nucl. Sci.* (2011)

SPAWAR Experiments Looked for Nuclear Products

- Research effort at SPAWAR Systems Center Pacific began shortly after Pons and Fleischmann announcement and ended in 2012
- Used a palladium-deuterium co-deposition process to prepare the electrodes, seeking more reproducible results
- Experiments focused on finding the nuclear products from nuclear reactions occurring in electrolytic cells
- Used CR-39 solid state track detectors to look for tracks left by energetic particles

Mosier-Boss *et al.* Final Report 2016

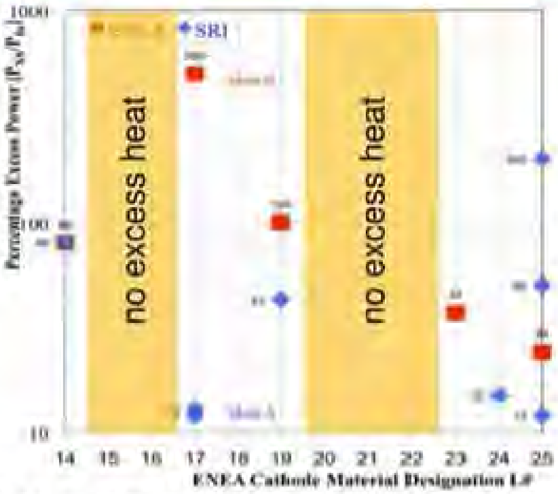


Triple tracks caused by breakup of ^{12}C into 3 ^{4}He due to collision with a fast neutron, SPAWAR analysis ends at visual inspection, similarity to deuterium-tritium fusion

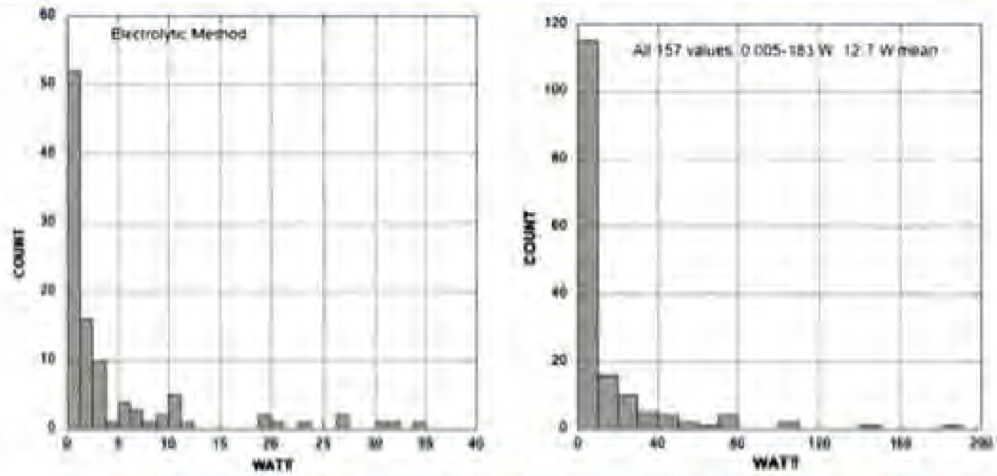
- Experiments were able to replicate CR-39 tracks, but noticed striking differences when compared to CR-39 exposed to fast neutron sources

SPAWAR CR-39 neutron measurements leave many unanswered questions.

Attempts to Address Reproducibility Yielded Erratic Results



McKubre *Proceedings of ICCF* (2009)



Summary of Electrolytic Cell reports from 1998-2004

Storms *Naturwissenschaften* (2010)

- Stanford Research Institute (SRI) and Italian National agency for new technologies, energy and sustainable economic development (ENEA) experiments try to address reproducibility using identically prepared samples from the same lot.
- 50% of trials showed no excess heat, while others showed variability of 500%.
- Observations of excessive heat were still erratic.

- Plot above was used by [Storms 2010] to demonstrate successes of LENR experiments
- Most striking feature is the large number of null results

Predictability and reproducibility are still outstanding issues with LENR

Summary

- After almost 30 years, the same issues are still present with cold fusion or LENR claims
  - Interesting anomalous effects exist that are difficult to reproduce and control
  - Lack of theoretical understanding for the underlying processes
  - Lack of independent testing and substantiation
- U.S. is involved in LENR research at universities, government labs, industry, and the private sector.
- It is premature to invest heavily in LENR research due to the status of knowledge, reproducible evidence, and technology currently available

Back up

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Transmutation Involves the Electroweak Force and Is a Nuclear Reaction, But Not Fusion

- Transmutation changes an atom from one element to another, which is accomplished by altering the number of protons

Free Neutron Decay

$$\mathrm{n} \rightarrow \mathrm{p}^{+} + \mathrm{e}^{-} + \bar{\nu}_e$$

Beta Decay

$${}^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + \mathrm{e}^{-} + \bar{\nu}_e$$

Inverse Beta Decay/Electron Capture

$${}^{26}_{13}\mathrm{Al} + \mathrm{e}^{-} \rightarrow {}^{26}_{12}\mathrm{Mg} + \bar{\nu}_e$$

- For isotopes unstable to these reactions, they spontaneously occur and release energy

- Widom and Larsen posit that localized condensed matter electric fields in metallic hydride surfaces can create "heavy" electrons (~20× e^- rest mass)
- The "heavy" electrons are captured by the metal and the resulting neutron is ejected
- These low momentum neutrons catalyze chains of nuclear reactions, e.g.

$$\begin{gathered} {}^{6}_{3}\mathrm{Li} + \mathrm{n} \rightarrow {}^{7}_{3}\mathrm{Li}, \\ {}^{7}_{3}\mathrm{Li} + \mathrm{n} \rightarrow {}^{8}_{3}\mathrm{Li}, \\ {}^{8}_{4}\mathrm{Be} \rightarrow {}^{8}_{4}\mathrm{Be} + \mathrm{e}^{-} + \bar{\nu}_e, \\ {}^{8}_{4}\mathrm{Be} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He}. \end{gathered}$$

$$Q\{{}^{6}_{3}\mathrm{Li} + 2\mathrm{n} \rightarrow 2\,{}^{4}_{2}\mathrm{He} + \mathrm{e}^{-} + \bar{\nu}_e\} \approx 26.9\ \mathrm{MeV}$$

Electric fields to create "heavy" electrons would require $E \approx 10^{11}$ V/m (ICF lasers produce electric fields up to ~10^{13} V/m).

In 2002 Iwamura *et al.* Observed Transmutation and Excess Heat in a D_2-Pd System

- Deuterium gas is permeated through a multilayer substrate of palladium and calcium oxide at 343 K for a week
- A thin film of cesium was added to the substrate, and Iwamura *et al.* report that the cesium layer decreased commensurate with an increase in praseodymium, along with x-rays from 10 to 100 keV, and excess heat
- Iwamura *et al.* propose an electron capture theory to create a di-neutron

$${}_{1}^{2}\mathrm{D} + \mathrm{e}^{-} \rightarrow {}_{0}^{2}\mathrm{n} + \nu$$

- The di-neutron can then create an element unstable to beta decay via neutron capture

$${}_{Z}^{A}\mathrm{X} + {}_{0}^{2}\mathrm{n} \rightarrow {}^{A+2}_{Z}\mathrm{X} \xrightarrow{\mathrm{e}^{-}} {}_{Z+1}^{A+2}\mathrm{Y}$$

- Via a chain of four of these reactions cesium could be converted to praseodymium
- No reported observations of the other elements in the chain
- No rigorous development of this theory to check if these reactions are energetically favorable
- NRL was unable to independently reproduce these results (2009)
- [Hioki *et al.* 2013] was able to reproduce these results

Hioki *et al.* measured 10^{-10} g/cm^2 of transmuted praseodymium after 250 hours of permeation treatments.

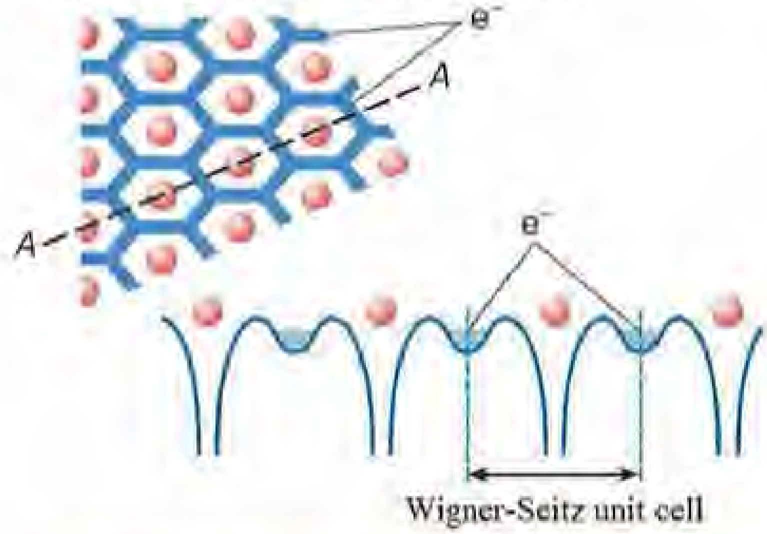
Ultra-Dense Deuterium: Origin in Rydberg Matter (RM)

- Rydberg atom – valence shell electrons are in highly excited state
- Cluster of Rydberg atoms can condense to form Rydberg matter
- In Rydberg matter, highly excited electrons become delocalized and act as a collective neutralizing background
- Rydberg matter is sparse, largest observed cluster had 91 atoms
- Bond distance d is given by:

$$d = 2.9\, n^2\, a_0$$

where n is principal quantum number and $a_0 = 5.2 \times 10^{-11}$ m is the Bohr radius

Winterberg *J. Fusion ENergy* (2010)

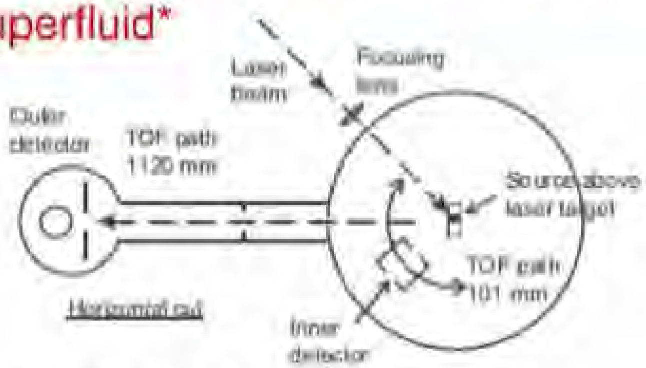


Rydberg Matter schematic electron distribution

- Rydberg matter has been formed from H, N, K, and Cs

Ultra-Dense Deuterium is Claimed to Have Remarkable Properties

- Exotic form of Rydberg matter where nuclei act as the delocalized electrons
- Bond distance - $d = 2.3 \times 10^{-12}$ m
- Density - $130{,}000\ \mathrm{g/cm^3}$ (compare to density of lead - $11.34\ \mathrm{g/cm^3}$)
- Room temperature super conductor*
- Superfluid*



Setup for TOF Experiments
[Badiei *et al. Physica Scripta* (2010)]

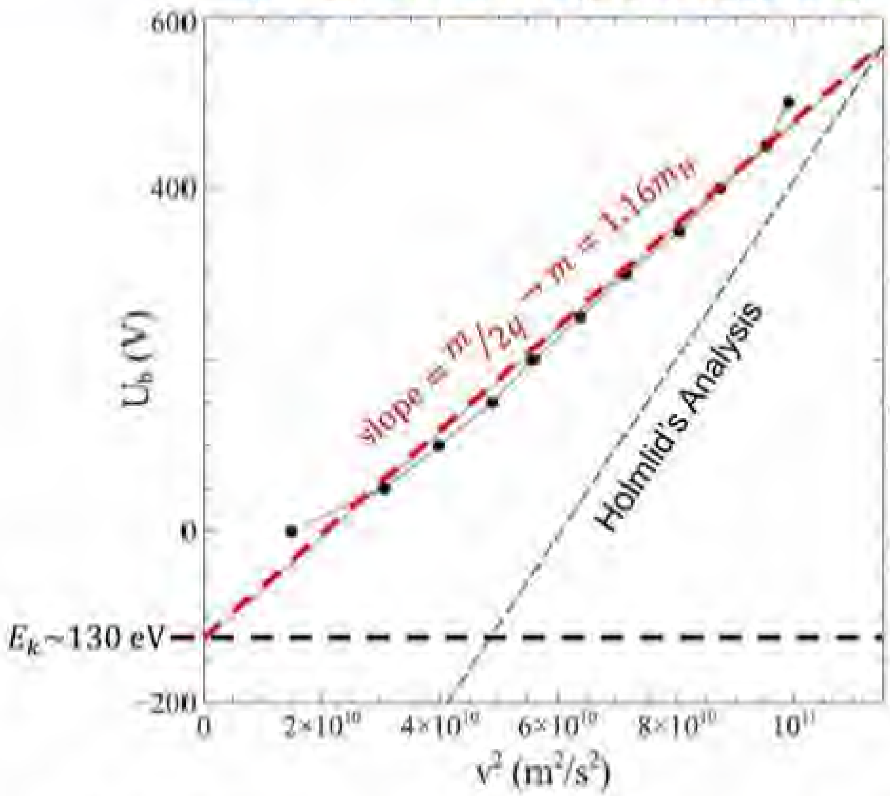
- Nuclei of comets covered in RM
- Stable exospheres on Moon and Mercury explained by heavy RM
- RM is part of dark matter
- RM could explain Faraday rotation in intergalactic space

*Predicted by theory [Berezhiani *et al.* 2010], not experimentally verified

Presented evidence for existence of ultra-dense deuterium is time-of-flight mass spectrometry, claims do not match available evidence

Reanalysis of TOF Data Leads to Contradictory Results

[Hansen *Int. J. Mass Spectroscopy* 2016]*



*Holmlid's comment on Hansen's comment was rejected by the journal

- Hansen reanalyzed TOF data using Holmlid data
- Laser ionizes RM, leading to Coulomb explosion
- Conservation of energy gives

$$\frac{m}{2q}v^2 = U_b + \frac{1}{q}E_k$$

- Holmlid assumes energy goes into rotational excitation, such that $E_k =$ 630 eV
- Hansen analysis indicates data is more consistent with Hydrogen molecules being involved in Coulomb explosions, not Deuterium

Hansen analysis casts doubts on validity of Holmlid interpretation

Major caveat: Research on Ultra-dense Deuterium is Limited to One Small Group

- Work is published in mainstream, reputable journals
- ~94% of the 84 articles were written by 4 authors in the same group headed by Leif Holmlid
- ~88% of citations are self-citations
- No other group has reproduced the results
- No other experimental group has published a paper on ultra-dense deuterium

Measurements has not be independently reproduced.

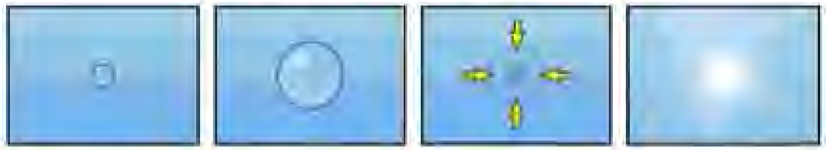
Acoustic Cavitation Fusion

- Cavitation is the process of boiling a liquid as a result of pressure reduction
- When the bubbles that form collapse, a shock wave can form capable of causing damage, e.g. pitting on a propeller

Damaged Boat Propeller

https://en.wikipedia.org/wiki/Propeller

Sonoluminescence

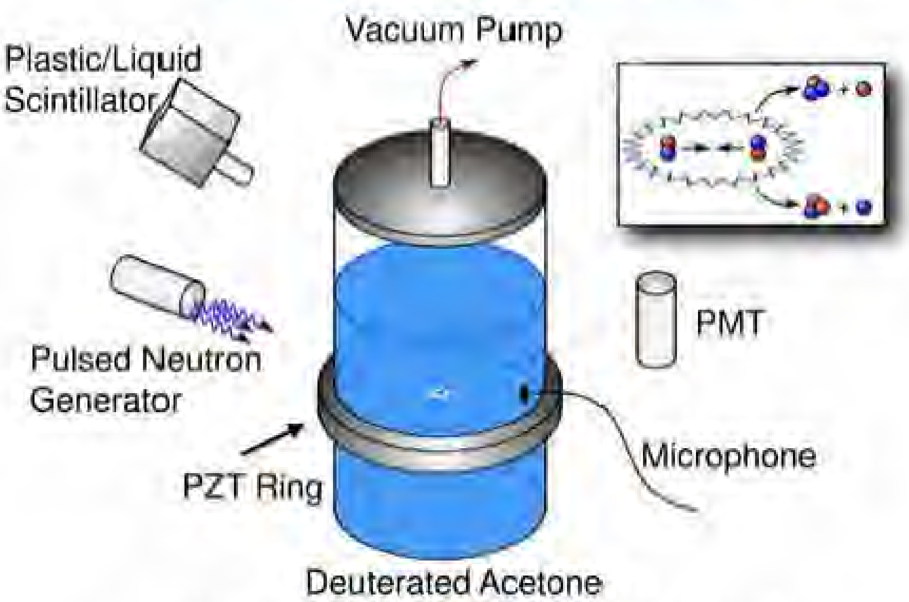


https://en.wikipedia.org/wiki/Bubble_fusion

- Sonoluminescence is the generation of light from cavitation due to sound waves
- Acoustic cavitation fusion seeks to use these shock waves to locally heat the liquid to produce a plasma and stimulate fusion reactions

Acoustic Cavitation Fusion – Discredited Observations

[Taleyarkhan *et al.* 2002]



https://en.wikipedia.org/wiki/Bubble_fusion

- Taleyarkhan *et al.* claim to have observed neutrons coincident with sonoluminescence indicative of fusion

- Internal attempts at reproduction failed to produce detectable neutrons
- External efforts by Putterman at UCLA also failed to reproduce Taleyarkhan's results
- [Naranjo 2006] demonstrates that neutron spectra reported by Taleyarkhan not consistent with D-D fusion, but with ^{252}Cf source.
- An "independent confirmation" [Xu and Butt 2005], which was later determined that Taleyarkhan was deeply involved and led to findings of falsification and research misconduct

Discredited observations notwithstanding, extreme conditions do exist in collapsing bubbles

Acoustic Cavitation Fusion – Plausible in Simulations

- Single Bubble Sonoluminescence (SBSL) has led to greater experimental control and more extreme conditions
- Spectroscopic studies on SBSL measured heavy-particle temperature and pressure of 15000 K and 4000 atm
- Observations of noble gas ion emission lines demonstrate plasma formation
- Detailed SBSL Ar line profile analysis has estimated electron densities of 10^{21} cm^{-3} at 3.8 bar of acoustic driving pressure
- Simulations show densities up to 10^{22} cm^{-3} and temperatures up to 10^{8} K

SBSL of Xenon in Sulfuric Acid

Flannigan and Suslick *Nature* (2005)

- **Extreme conditions short lived ~10^{-12} s**