A New Way of Triggering Nuclear Fusion

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If Neil Sedaka thought breaking up was hard to do, he hadn't tried *fusion*!

Fission

Though fusion was first believed to power the Sun a century ago, it took decades to unravel its secrets and we've yet to control it. Alternatively, it took barely 4 years from the discovery of uranium nuclear fission in Germany in 1938 to the first nuclear "pile" in Chicago, IL in 1942. Presently, 440 fission reactors are operating across the planet. Fission power makes gigawatt levels of power with zero carbon emissions and can create abundant hydrogen for a future hydrogen economy. Yet, fission, for all its promise beginning with President Eisenhower's "Atoms for Peace" in the 1950s, has remarkable downsides. These downsides include nuclear waste disposal of products with long half-lives, uranium enrichment security, and devastating accidents like Chernobyl and Fukushima Daiichi, leaving whole areas uninhabitable. Consequently, NASA has looked to fusion as an alternate power source.

Fusion

It had long been thought that fusion, or the fusing of light isotopes into heavier ones, would provide clean nuclear power. Fusion follows the recipe of $E=mc^2$, where the energy comes from the mass difference between the reactant and product masses. Afterall, the sun does it with impunity! Gravitationally-assisted fusion takes advantage of the Sun's large 1.4 million km diameter, a core density 150 times that of liquid water and a cozy temperature of 15.7 million degrees Kelvin (K).

On Earth, we lack the size, fuel density and temperature to invoke, let alone use, classic stellar fusion. One needs to achieve a critical level of fuel density, confinement time, and plasma temperature or Lawson Criteria [1] to achieve net positive energy output. In the 1950s, various magnetic confinement fusion (MCF) devices, including Sakharov's tokamak and Spitzer's Stellarator, came along. Each tried the near impossible: heat a gas hot enough to become a plasma, further heat the plasma by magnetically squeezing it, then drive it to fusion, and ignition. *Just don't let it escape*. Inertial Confinement Fusion (ICF) followed once lasers and ion beams were available to ablate the surface of a target, compressing it via direct drive implosion, or indirectly by x-rays. Unlike MCF, ICF fusion reactions last less than a microsecond before the target disassembles ending the reaction. Both devices create fusion but with insufficient energy to offset initiating and maintaining nuclear reactions. Other means were tried including coupling MCF and ICF together as Magneto-Inertial Fusion (MIF) where an ICF target is held together longer by a synchronized magnetic field. Meanwhile, efforts continue with the International Thermonuclear Experimental Reactor (ITER) in France, the National Ignition Facility (NIF) in the US, and several others.

Hot fusion is challenging for several reasons. First, one must overcome the Coulomb Barrier, where the positive charges of the fusing ions repel one another. This condition gives rise to the very small fusion cross-section, σ_f, or the probability that two particles, like the heavy hydrogen isotope deuterium (D) and the heavier hydrogen isotope tritium (T), will fuse into an alpha particle, or helium nuclei. Second, although the fusion probability is enhanced by increasing the plasma temperature towards 100 million degrees K, MCF requires ever stronger and power-hungry magnets since no material can withstand those temperatures.

MCF, ICF and MIF rely upon fusion alpha particles to heat the plasma, drive the nuclear reactions and provide power gain. Yet, NASA's theoretical treatment by Pines *et al* [2] showed the limitation of Coulomb-induced, small-angle scattering of these particles where they barely graze each other. In most cases, the alphas and deuterons skip past each other with little energy transfer. Ideally, fusion benefits by a pre-ponderance of large angle scattering interactions, or "direct hits", with increased momentum transfer to increase nuclear reaction rates.

Although there are various fusion cycles like proton-proton (p-p), proton-boron (p-^{11}B, or “tri-alpha”), and the nuclear catalytic carbon-nitrogen-oxygen (CNO) cycles, the ones most often used terrestrially are:

D(d,n)^{3}He where a deuterium atom (D) or a deuterium nucleus, deuteron (d) fuse freeing a neutron (n) and producing a helion (^{3}He).

D(d,p)T where the (D) and (d) fuse freeing a proton and producing a triton (T).

These two reactions have nearly equal probability. However, a secondary DT reaction:

D(t,n)^{4}He where the (D) and triton (t) fuse resulting in a neutron (n) and a ^{4}He or alpha,

has 100x the probability of fusion as the DD reaction, provided one supplies the radioactive tritium.

A DT fusion neutron has 14.1 MeV kinetic energy and the ^{4}He alpha has 3.5 MeV of kinetic energy. Unfortunately, ¾ of the fusion energy leaves the reaction volume with the fast neutrons! Fast, uncharged neutrons are difficult to stop, yet for a viable reactor they need to be captured to breed more tritium fuel, and ideally, *not be captured* by the reactor components. Fast neutrons rob plasma energy and may both activate and displace reactor wall nuclei, weakening the wall. Though these activation half-lives are less than fission waste half-lives, they pose challenges to reactor operation. A viable fusion reactor must solve these technical problems.

Although nearly all conventional fusion reactors expect to use the DT cycle, due to the higher fusion cross-section, no fusion reactor has shown net power gain. It takes far more energy to power magnets or lasers than has been extracted as thermonuclear energy. Furthermore, the source of the copious amount of tritium is unresolved. Currently, tritium is produced in a fission reactor! Despite spending billions of dollars, we aren’t close to a fusion energy source.

Some fusion power observers have quipped, “Fusion is twenty years off and always will be.”

NASA’s Need

Just as we have terrestrial energy needs, NASA has significant energy needs for deep space travel and colonizing either the Moon or Mars. For over 60 years space power has come from photovoltaic cells, [3] fuel-cells [4], or Radio-Thermal Generators (RTGs) [5] that use non-fissile plutonium, ^{238}Pu. Their success is unmatched having powered both Voyager probes that are now in interstellar space. However, RTGs thermoelectrically convert heat to electricity with a limited 7.5% efficiency. Although the resulting heat keeps spacecraft warm, whether on Mars or in transit to the outer planets, there is a far greater power need. The Advanced Stirling Engine [6], which converts thermal energy to piston power driving an electric generator, increases efficiency by a factor of three. That can either reduce the ^{238}Pu mass or increase the electrical output. Although the system has shown great promise in NASA tests, it has yet to be flown in space. Nuclear Electric and Nuclear Thermal Propulsion provide great efficiencies over chemical rockets, yet over 1 MW thermal (1 MWt) is required. The KiloPower fission reactor [7], successfully tested in Nevada in 2018, may produce 10 kW electric (43 kWt). NASA is evaluating it for nearer term missions, but it uses highly enriched uranium with additional launch safety and security concerns and costs.

Again, fusion is a possible alternative either on its own, or as a hybrid fusion reaction driving a fission reaction. It has long been noted that, “Fusion reactors are 'neutron rich' and 'power poor' while fission reactors are 'neutron poor' and 'power rich'” [8]. A hybrid technology would make the best of both worlds: fast fusion neutrons fission actinides whether or not they are fissile. This fusion-fission cycle may allow the use of natural or low-enriched uranium with the obvious nuclear non-proliferation and flight safety benefits. For instance, just the safety costs of handling an RTG’s ^{238}Pu exceeds $20M per launch, neglecting the additional cost of producing ^{238}Pu.

Lattice Confinement Fusion

Whereas an MCF plasma is limited to 10^{14} ions/cm^3 and ICF can momentarily reach 10^{26} ions/cm^3, some metals can indefinitely hold hydrogen isotopes approaching 10^{23} ions/cm^3 at room temperature. The resulting hydrided or deuterided metals form a cold, neutral quantum plasma, where the electrons are Fermi degenerate. Rather than require massive magnets to contain a hot plasma, the metal atoms themselves confine and maintain a cold plasma under conditions found in conductive metals, gas giant planets and White Dwarf Stars. Fusion rates are dependent upon density as well as temperature.

Each of the previous modes of fusion: magnetic, inertial and the combined magneto-inertial either confine a very hot plasma with large magnets or briefly create it with larger lasers. Building upon years of experience with deuterided metals, NASA researchers found ways to trigger fusion reactions in these metals and coined the term Lattice Confinement Fusion (LCF). LCF emphasizes the use of a lattice to hold deuterons at high density where the metal lattice atom's electrons screen the positive D^+ charges. This electron screening shields both deuterons from each other and allows charged fusion products to more efficiently transfer momentum by large-angle scattering. Electron-screened ions are able to approach one another more closely increasing the nuclear strong force fusion probability by tunneling through the Coulomb Barrier. However, the D^+ ions require a minimum energy to start the process.

A Match to Light the Fusion Fire

NASA [9] lit the fusion fire by irradiating ambient-temperature deuterated metals with moderate-energy gamma rays. Gamma rays initiating the process were created by a Dynamitron electron beam accelerator with a tantalum braking target. Small vials (the size of one's thumb, Figure 1) containing either titanium deuteride (TiD_2) or erbium deuteride (ErD_3) were exposed to photon beam energies of up to 2.9 MeV.

Figure 1 Photo of small vials containing Erbium deuteride fuel radiated by the gamma beam to investigate Lattice Confinement Fusion.

The resulting nuclear process is illustrated in Figure 2 below. Part (A) in the figure shows a lattice of erbium loaded with deuterium (i.e., erbium deuteride), which exist as individual ionized deuterons. Upon irradiation with a photon beam, a deuteron dissociates, ejecting the neutron and proton. The neutron collides with another deuteron, accelerating it as an energetic "d*" as seen in (B) and (D). The "d*" induces either screened fusion (C) or screened Oppenheimer-Phillips (O-P) stripping reactions (E). In (C), the energetic "d*" collides with a static deuteron "d" in the lattice, and they fuse together. This fusion reaction releases either a neutron and helium-3 (shown) or a proton and a triton. These fusion products may react in subsequent nuclear reactions, releasing more energy. In (E), a proton is stripped from an energetic "d*" and is captured by an erbium (Er) atom and converted to a different element, thulium (Tm). If the neutron instead is captured by Er, a new isotope of Er is formed (not shown). All of these nuclear reactions produce useful energy. Turning off the electron accelerator safely stops the reactions. The experimental observations and the theory behind those observations were published in *Phys Rev C* in 2020 [2,9]

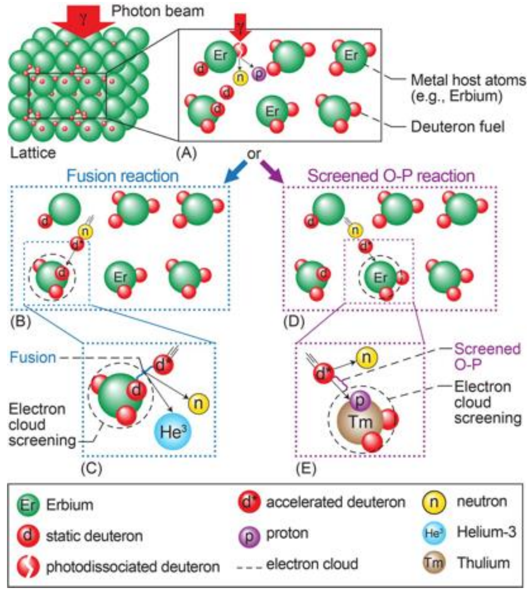

Figure 2 Gamma Ray initiated Lattice Confinement Fusion.
See also the NASA Web Site [12] for an animation of the reaction process.

NASA Demonstrates Lattice Confinement Fusion

Once the cold deuterons heat and fuse as illustrated in Figure 2, the 2.45 MeV fusion neutrons can be detected by neutron spectroscopy. Both initial uncharged photo-neutrons and fusion neutrons effectively accelerate (or heat) deuterons imparting up to 4/9ths of their energy to deuterons via large angle scattering collisions. Charged particle fusion products, like protons and alphas, further heat the D-fuel where screening increases their energy transfer approaching uncharged neutron heating efficiency.

The titanium and erbium atomic electrons screen the positively charged deuterons allowing them to approach closer despite the Coulomb Barrier. Electron screening has been experimentally shown to increase fusion rates by several orders of magnitude as if the deuterons had as much as 1 kiloelectron volt (keV) or more of additional kinetic energy. One keV has the equivalent temperature of 11 million degrees Kelvin, yet, the metal lattice housing the deuteron fuel is much cooler.

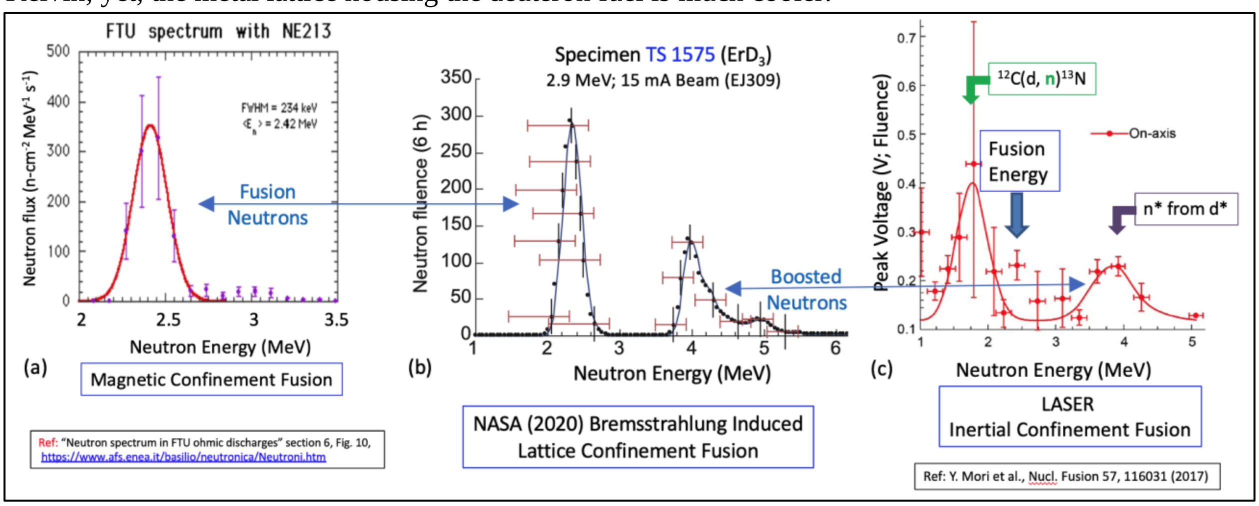

Figure 3:Comparison of neutron spectra: (a) shows the MCF 2.45 MeV neutron spectrum correlated with the 3(b) LCF neutrons; 3(c) shows example ICF fusion energy and boosted neutrons (~4MeV) correlated with 3(b) LCF ~4-5 MeV neutrons.

Figure 3 shows a comparison of three neutron spectra; one resulting from MCF (3a), one resulting from NASA's LCF (3b), and one resulting from ICF (3c). After postprocessing the neutron spectroscopy data and extensively removing any gamma influence, the neutron data was plotted as counts vs energy (Figure 3b). The major peak in the spectrum corresponds to the 2.45 MeV fusion peak (similar to MCF neutrons) with two higher energy peaks at ~4 and ~5 MeV (similar to ICF neutrons). The latter may be the result of either boosted fusion or other processes such as screened Oppenheimer-Phillips stripping reactions [10,11] due to the highly screened metal lattice environment. The combined fusion and higher energy neutrons provided NASA a glimpse into possible means for achieving process multiplication and net energy gain.

Neutron Spectroscopy Diagnostics

Different neutron recoil spectrometers were used including hydrocarbon-based Eljen liquid and Inrad Optics Stilbene solid scintillators where an incident neutron scatters off the hydrogen and carbon atoms producing light pulses. Using sensitive photodetectors, these sub-microsecond photon flashes allowed the incident neutron energy to be calculated (mathematically unfolded [13]) based upon the detector's response function. Because the enormous gamma ray flux interfered with neutron measurements the detectors were housed in a massive lead "cave" that also scattered 80% of the neutrons away from the detectors. The Los Alamos National Laboratory Monte Carlo N-Particle version 6 (MCNP-6©) [14] nuclear modeling code was used to correct for these losses.

The Path Forward

NASA drove LCF externally by a photo-neutron source creating a sub-critical fusion reaction. There are other methods including using an isotopic neutron source, like AmBe or ^{252}Cf, to initiate the reactions. Once started, the reaction may be self-sustaining by using neutron reflectors. Similarly, coupling a fusion neutron source with fission fuel may take advantage of the best of both. Further development of the process is required to increase the efficiency of these lattice-confined nuclear reactions. Their applications range from terrestrial or long-duration space power to space propulsion to the production of radioisotopes, such as the most common medical isotope, ^{99m}Tc.

Furthermore, NASA developed and published results from lower threshold triggering of nuclear reactions while pumping deuterium gas through thin-wall palladium-silver tubing [15], and observed fast neutrons during the co-deposition of palladium and deuterium [16]. These efforts continue under the NASA Lattice Confinement Fusion Project using the real-time neutron spectroscopy [13] developed for, and deployed with, the aforementioned bremsstrahlung induced fusion campaign. Related electron-screened enhanced fusion was observed at the Lawrence Berkeley National Laboratory with Google Research funding [17]. More recently, the Department of Energy ARPA-E held a workshop on low energy nuclear reactions (LENR) in which NASA personnel participated [18]. ARPA-E is considering a solicitation to support seminal experiments to develop further insights into the physical reaction mechanisms.

Conclusion

NASA has demonstrated a repeatable new method of inducing nuclear fusion reactions without magnetic fields or lasers using deuterated metal lattices to hold high density fuel. The current work demonstrates the ability to create enhanced primary fusion reactions and secondary nuclear reactions that may increase power gain and move closer to the practical application of Lattice Confinement Fusion. If the reaction rates can be significantly scaled it may be a new path for realizing clean nuclear energy without long lasting radioisotopes, both terrestrially and in space. It may provide new means to create medical and industrial radioisotopes for diagnostics or medical treatments. Yet, there's much to be done to optimize what's been discovered to improve its efficiency and power gain.

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