Probing neutrons and purported fission daughter products from gas-loaded, laser-irradiated metal-hydrogen targets

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This article reviews a series of experimental reports that claim the observation of energetic neutrons and the formation of new low-atomic number (Z ≤ 30) elements in solid-state metal-hydrogen samples in out-of-equilibrium conditions (created, *e.g.,* via pressure/temperature cycling or laser irradiation). Reported new element formation is concomitant with morphological feature changes and, in some cases, new elements correspond to known fission daughter pairs of the involved metal lattice nuclei. Related experimental reports suggest that the elements found in the newly formed morphological features may have unnatural isotopic ratios, indicating a nuclear origin. The presented body of experimental reports suggests a hypothesized novel class of nuclear reactions, which has recently motivated the creation of a new research program by the US Department of Energy's innovation agency ARPA-E. Because of the absence of high-energy stimuli in such systems, ARPA-E refers to this hypothesized class of nuclear reactions as low-energy nuclear reactions (LENR). To help interested parties quickly gain insights into this research domain, we present a curated collection of experimental evidence reported to date, provide a theoretical explanation that is both consistent with these reports and rooted in established physics, and lay out a research roadmap.

1. Introduction

Nuclear reactions such as fusion and fission reactions are conventionally believed to be initiated by either the absorption of neutrons in atomic nuclei or by the transfer of comparatively large energies to nuclei (>keV level energies). In solid-state systems near room temperature, energy quanta present are typically on the order of eV, so nuclear reactions are not expected to be triggered in such systems in the absence of a neutron source (as in the case of a fission reactor). However, a sizable literature — comprising hundreds of experimental papers at this point[1] — suggests that a novel class of exothermic nuclear reactions may occur in certain room-temperature metal-hydrogen systems in out-of-equilibrium conditions. This implied class of nuclear reactions has been termed low-energy nuclear reactions (LENR).

The amount of attention that such reports have received has remained limited for several reasons: association with the 1989 "cold fusion" controversy has led to what the philosopher of science Huw Price called a "reputation trap"[2]; and a dearth of plausible theoretical explanations has resulted in the absence of systematic follow-on experimentation to clarify the discrepancies between reported empirical observations and conventional nuclear theory. The combination of the above factors led most of the major physics institutions to bypass LENR research. Consequently, scientific exploration in this area has largely been carried out by smaller groups often with minimal funding. The quality of reports has suffered from these circumstances.

After carefully reviewing the LENR literature that has accumulated to date, ARPA-E — the innovation agency of the US Department of Energy — has found this field to be worthy of further study[1,3,4]. ARPA-E identified the dearth of new experimental studies conducted to the highest scientific standard as a key bottleneck for progress in the field. This includes extensive data sets, state-of-the-art detectors, and ample controls. As stated by ARPA-E in the funding opportunity announcement of their LENR program[1]: *"LENR as a field remains in a stalemate where lack of adequate funding inhibits the rigorous results that would engender additional funding and more rigorous studies."* Resolving this stalemate is of high scientific and technical significance. As also stated by ARPA-E[3]: *"Based on its claimed characteristics, LENR may be an ideal form of nuclear energy with potentially low capital cost, high specific power and energy, and little-to-no radioactive byproducts."*

We have carefully reviewed LENR literature to date to identify an experimental platform that is suitable to incisively test LENR claims. This effort yielded what we consider to be the strongest indications of LENR effects in the existing literature that could be capable of breaking the stalemate identified by ARPA-E. By concisely showcasing thus identified articles and suggesting avenues for future research, we seek to streamline the debate and help interested parties to quickly gain an entry point into this research area.

We provide a hypothesis based on *coherently-coupled nuclear fusion-fission* to explain the suggested findings of these experimental reports and to provide a roadmap for refinement and advancement of these experiments. This hypothesis, as laid out in refs.[5–9], relies entirely on established physics principles. At the heart is the modification of reaction rates and reaction products as a result of nonradiative energy transfer between nuclei, induced by weak couplings and enhanced by collective effects (Dicke enhancement[10–13]). Similar mechanisms are increasingly employed and exploited in other areas of energy-related quantum engineering at the molecular, atomic, and nuclear level[14]. Advancing experiments and the corresponding theoretical picture outlined here can potentially lead to the development of new forms of advanced nuclear technology.

2. Focused literature review

We have carefully reviewed LENR literature to identify an experimental platform that we consider the most conducive for systematically probing claims of novel types of nuclear reactions occurring in certain metal-hydrogen systems.

We have specifically focused on reports with observables that are unambiguously nuclear in their origins. This led us to key in on: i) neutron emissions; and ii) new low-Z ($Z \leq 30$) elements with unnatural isotopic ratios. The samples that reportedly produce such effects are always solid-state metal hydrogen systems near room temperature. We further narrowed down possible experiments of interest by choosing studies of low complexity that report i) and ii), which are predominantly studies of gas-loaded palladium-deuterium and titanium-deuterium samples below 600 ^{o}C and 100 bar partial pressure of H_2/D_2. Many of these articles involve irradiation with an optical laser to stimulate non-equilibrium conditions in the sample. The literature suggests that, when laser irradiation is involved, the proposed configuration is effective in generating the sought observables at near-ambient conditions of ~25 ^{o}C and <2.5 bar.

A summary of key pieces of literature matching these characteristics are listed in Tables 1–3. Table 1 contains articles that report the observation of neutron bursts significantly above background and Table 2 articles that suggest the production of low-Z elements. Table 3 contains related articles that report observations of unnatural isotopic ratios of Pd and low-Z elements on treated samples. Fig. 1 contains a selection of reported results.

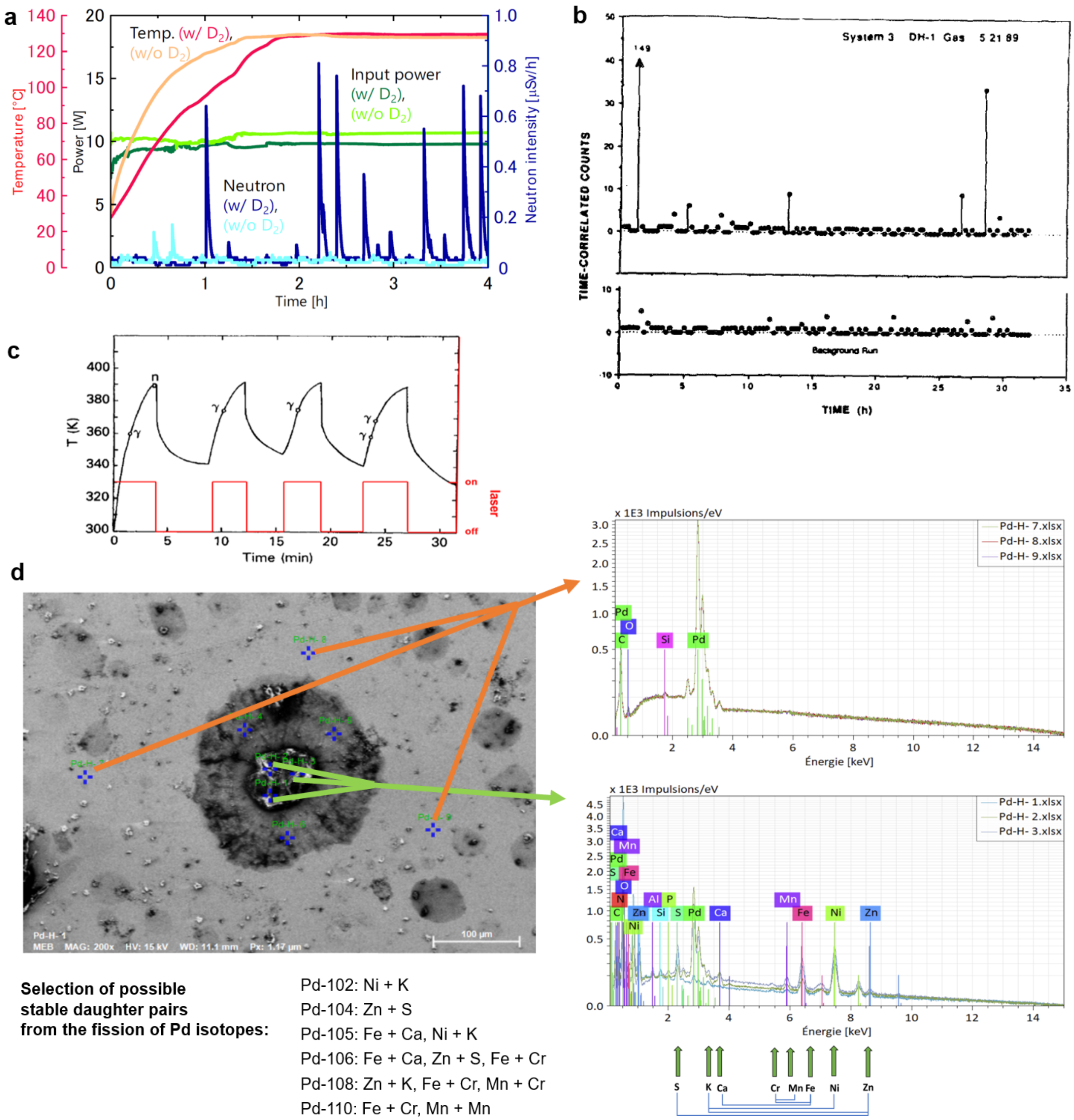

Fig. 1. a) Neutron bursts from a gas-loaded PdD sample under 2 bar partial D pressure with no laser irradiation. Adapted from ref.[15]. b) Top: neutron bursts detected by a neutron counter near a gas-loaded PdD sample under 60 bar partial D pressure with no laser irradiation. Bottom: simultaneous neutron background far from the sample. Adapted from ref.[16]. c) Suggestive time-correlation between Nd:YAG laser irradiation and observed neutron and gamma bursts (weak statistics). Adapted from ref.[17]. d) Morphological changes and corresponding elemental changes in the region of interest on the surface of a gas-loaded PdDH sample after 90 days of laser irradiation. Adapted from ref.[18]. Observed elements are consistent with possible stable daughter pairs from the fission of Pd isotopes as indicated. Consistent with reported results in Table 3 and the Fe, Ca, Cr, and Zn peaks in[13,15,18,19] are, for instance, the reactions Pd-108 → Fe-54 + Cr-54; Pd-108 → Zn-64 + Ca-44; Pd-102 → Fe-54 + Ca-48, among others.

Table 1. LENR publications that report neutron emission. Shaded experiments with laser irradiation and moderate temperature/pressure. Unshaded experiments without laser irradiation and with high temperature/pressure.

Article	***Journal***	***Sample***	***Temp.***	***Pressure***	***Laser irradiation***	***Neutron detector***	***Neutrons reported***	***Elemental analysis conducted/ New elements reported***
Ninno et al. 1989[19]	Europhysics Letters	TiD	-196°C	50 bar	No	BF3 neutron counter	Bursts up to 500x above background	No/NA
Fralick et al. 2020[20] (experiment conducted in 1989)	Int. J. of Hydrogen Energy	PdAgD	300-400°C	7-14 bar	No	Detector type not specified	Neutron burst reported but not recorded	**Yes/Yes**
Menlove et al. 1990[16]	Journal of Fusion Energy	PdD and TiD	-30°C	3-69 bar	No	Multiple He-3 neutron counters	Bursts up to 350x above background	No/NA
Jorne 1991[21]	Fusion Tech.	PdD	-80-320°C	up to 91 bar	No	2 liquid scintillator neutron counters	Bursts up to 20x above background	No/NA
Beltyukov et al. 1991[17]	Fusion Tech.	TiD	25-500°C	0.01-4 bar	Nd:YAG, 1060 nm, 1 J/1 µs pulses at 33 Hz, 0.13 cm^2 spot	Multiple He-3 neutron counters	Bursts up to 18x above background	No/NA
Nassisi 1998[22]	Fusion Tech.	PdD	25°C	2.3 bar	XeCl excimer, 308 nm, 1 J/20 ns pulses at 2 Hz, 2 cm^2 spot	Boron-lined neutron counter	Bursts up to 20x above background	**Yes/Yes**
Mastromatteo 2016[23]	JCMNS	PdD	25°C	1.5 bar	1) Diode, 405 nm, 3 mW, 1 cm^2 spot; 2) He-Ne, 633 nm, 9 mW, 1 cm^2 spot	Detector type not specified	Neutron burst reported but not recorded	**Yes/Yes**
Uchikoshi 2020[24]	Kyoto U. thesis	PdD	80-170°C	2 bar	1) Nd:YAG, 1064 nm, 50 mJ/10 ns pulses at 10 Hz, 0.05 cm^2 spot; 2) Diode, 405 nm, 50 mW; 0.05 cm^2 spot; 3) Diode, 594 nm, 30 mW, 0.05 cm^2 spot	Methane-nit rogen neutron counter	Bursts up to 40x above background	No/NA

Table 2. LENR publications that report new elements. Shaded experiments were performed with laser irradiation and moderate temperature/pressure; unshaded experiments without laser irradiation and high temperature/pressure.

Article	***Journal***	***Sample***	***Temp.***	***Pressure***	***Laser irradiation***	***Elemental analysis***	***New elements reported***	***Neutrons monitored/ Neutrons reported***
Fralick et al. 2020[20] (experiment conducted in 1989)	Int. J. of Hydrogen Energy	PdAgD	300-400°C	7-14 bar	No	ICP-AES, EDX, SIMS	Cr, Cu, Fe, Zn	**Yes/Yes**
Nassisi 1998[22]	Fusion Tech.	PdD	25°C	2.3 bar	See Table 1	EPMA	Al, Ca, Fe, Mg, S, Si, V, Zn	**Yes/Yes**
Nassisi & Longo 1999[25]	Fusion Tech.	PdD	25°C	2 bar	Same as Nassisi 1998	EDX, ICP-MS	Zn	No/NA
Mastromatteo 2016[23]	JCMNS	PdD	25°C	1.5 bar	See Table 1	EDX	Al, Ca, Cl, Fe, Si, Zn	**Yes/Yes**
Barrowes et al. 2022[26]	ICCF24	PdD	25°C	2 bar	1) Diode, 640 nm, 5 mW, pulsed at ~11 MHz, 0.2 mm^2 spot; 2) Diode, 405 nm, 20 mW, pulsed at ~100 kHz, 0.2 mm^2 spot	EDX	Al, Ca, Fe, Ni, S, Si, Zn	No/NA

Table 3. LENR publications that report changes in isotopic ratios.

Report	***Institution***	***Sample***	***Analysis technique***	***Reported isotopic ratio changes between treated and untreated sample***	***Elemental concentration changes between treated and untreated sample***
Mizuno et al. 1996[27]	Hokkaido U.	PdD	EPMA, ICP-AES, EDX, SIMS	51% decrease in Pd-108 to Pd-110 ratio; 748% increase in Cr-54 to Cr-52 ratio	
Mo et al. 1998[28]	Tsinghua U.	PdD	NAA	34% increase in Zn-64 to Zn-68 ratio	Increase of Zn content from 0% to 30% (in 10 mg Pd sample)
Bush & Lagowski 1999[29]	EPRI	PdD	NAA	28±21% decrease in Pd-108 to Pd-110 ratio	5.4x increase of Cr content, 56x increase of Fe content, 12x increase of Zn content
Nassisi & Longo 1999[25]	U. of Lecce	PdD	EDX, ICP-MS		8x increase of Zn content
Passell & George 2000[30]	U. of Texas	PdD	NAA	24±11% decrease in Pd-102 to Pd-110 ratio	14x increase of Zn content
Passell 2006[31]	U. of Texas	PdD	NAA	8.9±0.1% decrease in Pd-108 to Pd-110 ratio	

To gauge the credibility of cited literature, the reported results are briefly reviewed here in view of alternative explanations. For reported neutron bursts, the possibility of neutrons from natural phenomena should be considered. Reported background neutron counts correspond to expected neutron fluences (<1/min/cm^2) from cosmic radiation[32,33]. Solar flares and extreme weather phenomena can lead to increased neutron counts, however, with increases typically below 50%[34] (solar flares) or as rare isolated bursts[35,36] (lightning). Typical uncertainty windows for mean background levels in neutron counters are <±15%[37]. Neutron bursts reported in Table 1 range from 1,800% to 50,000% increase relative to background means during periods from seconds to minutes. In some experiments such as Menlove et al. at Los Alamos[16], neutron measurements were done with redundant detectors positioned far from the sample to control for variation in neutron background.

Shifts in isotopic ratios are associated with nuclear reactions or with elaborate enrichment/depletion processes. Among the articles in Table 3, the most commonly used technique for isotopic analysis was neutron activation analysis (NAA). In the EPRI report[29], depletion of Pd-108 relative to Pd-110 by 28% is reported with an uncertainty window of ±21%. Natural variation in Pd isotopic ratios is below 0.01%[38]. However, the suggested shifts in Table 3 are subject to uncertainty and the reported evidence needs to be viewed as tentative and circumstantial.

Repeatability appears comparatively strong in the identified experiments as illustrated by Menlove et al.[16] reporting 42 runs with 14 runs yielding neutron bursts >3σ above background and Uchikoshi[24] reporting 53 runs with 29 runs yielding neutron bursts >3σ above background (30 runs without laser irradiation of which 11 runs yielded neutron bursts and 23 runs with laser irradiation of which 18 yielded neutron bursts). Nassisi and Mastromatteo anecdotally report high repeatability for the claimed elemental anomalies. In preliminary experiments, Barrowes has conducted two runs of the Mastromatteo experiment with each of the two runs yielding observations of new elements on the sample surface at sites of crater-like morphological features that were not present prior to laser treatment[26,39,40] (akin to Fig. 1d).

We consider the literature in Tables 1-3 sufficiently strong to motivate an experimental campaign. Nevertheless, none of these experiments have been replicated in separate labs with identical protocols and with comprehensive characterization and documentation of sample and stimulation characteristics.

3. Supporting hypothesis

LENR reports suggest two puzzling aspects in need of explanation: i) nuclear reactions—purportedly fusion reactions—appear to occur at unexpected rates; and ii) reported reaction products—whether particle emission or nuclear ash—vary in energy and/or character in ways that do not match expectations from canonical fusion or fission reactions. We propose that *coherently coupled fusion-fission* reactions could account for both accelerated rates of DD and HD fusion as well as induced fission of high-Z lattice nuclei such as Pd and Ti. Induced fission can comprise both asymmetric fission (neutrons or other energetic particles) and near-symmetric fission (low-Z element production). Since Pd disintegration requires excitation energies >20 MeV[41], we surmise that lattice-enhanced deuterium fusion reactions drive such fission in a coherent fusion-fission process. A detailed overview of this proposition has been reported[7,42].

Combined fusion-fission processes have been considered before. Bethe[43,44] suggested the use of energy released from DT fusion to trigger fission of U. In that case, the fusion and fission reactions are connected via energetic particles (neutrons) and can be analyzed as separate events with their own independent time constants. This is not the case if the fusion and fission processes are coherently coupled through shared oscillator modes. In that case, Terhune & Baldwin's 1965 PRL argument applies[10]: *"The solid, characterized by internal energy states of the nuclei, by the lattice vibrations, and by the electromagnetic field, is [to be] treated as an integrated quantized system rather than as a number of noninteracting* *nuclei. [..] The usual assumption that each nucleus radiates independently of other nuclei in the system is incompatible with the coupling of the nuclei through the common electromagnetic and phonon fields."* Nuclear transition rates are then calculated based on the time evolution of the corresponding Hamiltonian.

Naively, Bethe's fusion-fission model could be applied to the PdD lattice, where isolated DD reactions emit particles that drive fission reactions. However, in the isolated case where fusion and fission reactions interact only through energetic particles (radiative energy transfer), the DD fusion reaction would be much too slow to be observable (see Fig. 2a and 3a–b). For DD fusion reactions in particular, the consensus is that such reactions can occur inside a Pd lattice at rates up to about 10^{-40}/s per D pair[45–47]. This baseline rate requires close proximities on the order of D_2 molecules (74 pm), fluctuations on the order of 5 pm, and an electron screening potential on the order of 150 eV—conditions found in monovacancies of PdD[48–50].

However, reported observations of energetic particles such as neutrons imply rates $>10^{-20}$/s per D pair. In contrast to two-body rate calculations such as in Legget and Baym[51], Terhune & Baldwin proposed the acceleration of nuclear reactions in a solid lattice through coherent dynamics—so-called Dicke enhancement. An experimental demonstration of such Dicke enhancement at the nuclear level was first demonstrated in 2018: the nuclear decay of Fe-57 nuclei was accelerated proportional to the number of nuclei participating in a coherently coupled system[12]. We hypothesize that similarly, when D pairs are temporarily coupled to surrounding heavy nuclei through a coherent field (on a timescale of ns to μs), nonradiative transfer of energy can occur from the former to the latter. Because such a process is subject to Dicke enhancement, an acceleration of such dynamics can occur as a function of the number of nuclei that are coupled to the shared oscillator mode[11,13,42]. Coupling of nuclear states to electromagnetic oscillator modes has been demonstrated[52] and is known, for instance, as magnon-nuclear coupling. Transfer of nuclear excitation from one group of nuclei to a resonantly coupled group of nuclei has been demonstrated[53]. Extensive Dicke enhancement of such a process at the molecular level has been formally described[13,54].

The hypothesized asymmetric fission (*e.g.*, neutron emission) and near-symmetric fission processes are depicted in Fig. 2b–c. The model describing such a process is shown in Fig. 3c, along with the reaction rate that follows from evaluating the Dicke model Hamiltonian. In the described LENR systems, a shared field can be present between nuclei in the form of excited phonon modes. Because of the positive charge of nuclei, vibrational modes are experienced by nucleons as electromagnetic oscillations. Phonons can be caused in a lattice by diffusion of interstitial hydrogen[55,56] as well as by laser stimulation[57]. We point out that energy transfer via shared oscillator modes can be achieved even if the coupling field does not accommodate all energy that moves between donor and receiver systems[58]. Such nonradiative transfer dynamics follow directly from the well-established Dicke model—in contrast to radiative transfer where mediating particles must carry all transferred energy. Typical coupling strengths for magnon-nuclear coupling are on the order of $V = 100$ neV[52]. For such weak couplings to cause observable transfer effects, substantial Dicke enhancement of the transfer process is necessary. Fig. 3c illustrates a Dicke enhancement factor on the order of 10^9 that results from 10^{12} D pairs and 10^6 Pd-106 pairs coupled to the same oscillator mode. In a PdDx lattice with x=0.7, a volume of 6 μm^3 contains $\sim 10^{12}$ D pairs. Phonon and magnon modes can cover such volumes.

As shown in Fig. 3c, the key dependent variable in this research is the nuclear reaction rate. This variable is inferred from observed neutron counts and isotopic enrichment/depletion. Independent variables are those directly accessible experimentally. Intermediate variables describe nanoscopic conditions that are affected by the independent variables and which in turn affect the dependent variable. All variables are described in more detail below.

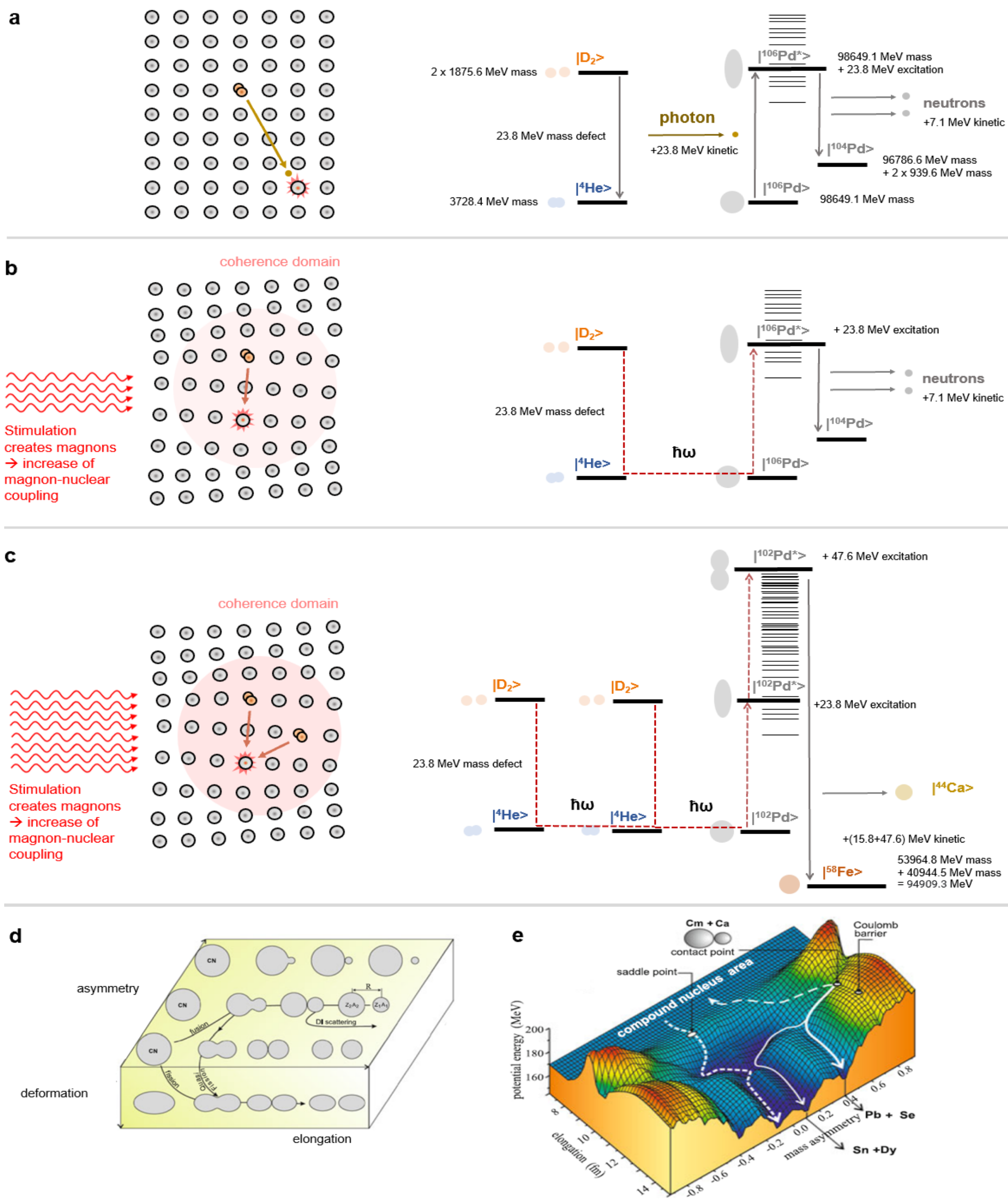

Fig. 2. a) Incoherent form of a coupled fusion-fission process (too slow to be observable). b) Coherent form of a coupled fusion-fission process (accelerated). c) With comparatively strong coupling/Dicke enhancement and long-lived (>1 ns) nuclear excited states available, lattice nuclei can get step-wise excited >40 MeV, leading to near-symmetric disintegration. Bosonic excitations including magnons or phonons could facilitate the process. d-e) Depiction of different asymmetric and symmetric decay pathways of a high-Z nucleus from high-energy excited states[59].

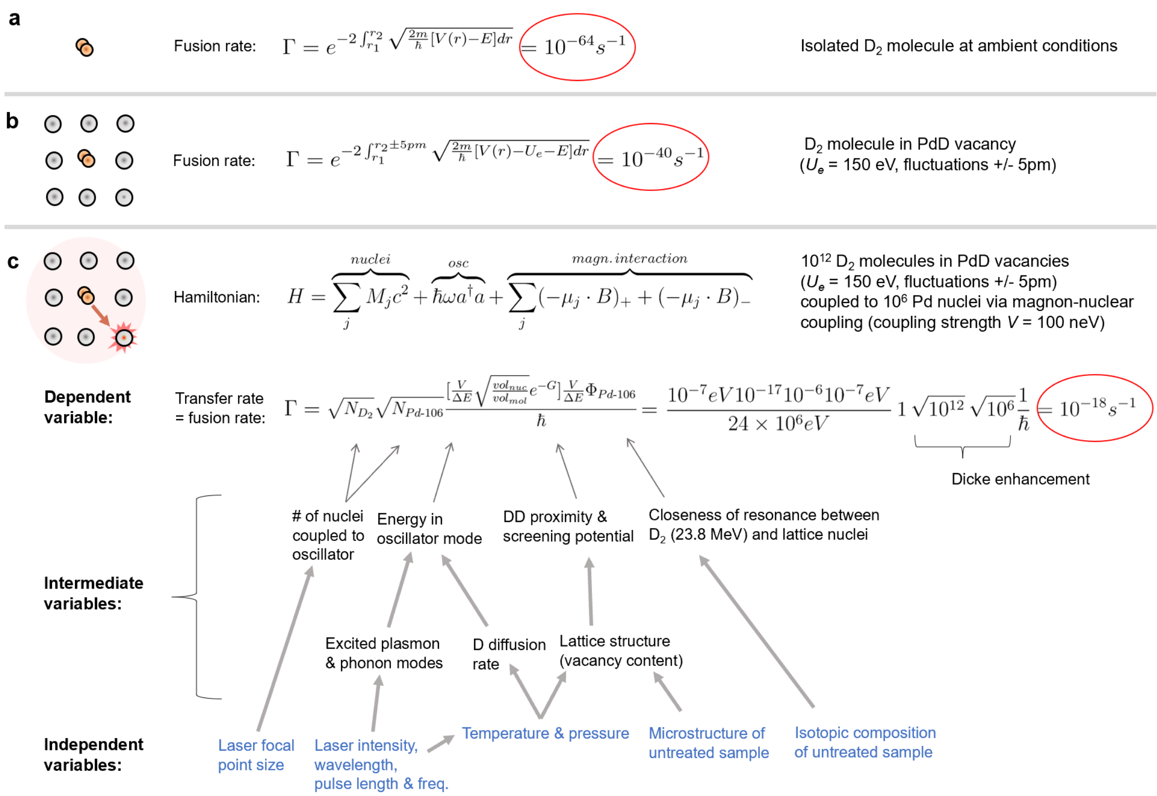

Fig. 3. a) Fusion rate estimate for incoherent DD fusion in a gas phase molecule[45]. b) Fusion rate estimate for incoherent DD fusion in a PdD vacancy[7,47]. c) Fusion rate estimate for coherent DD fusion coupled to Pd-106 nuclei[7,42] (note the close parallels to the model in[53]). Independent variables that are experimentally accessible (blue) are related to the fusion rate, which is the dependent variable.

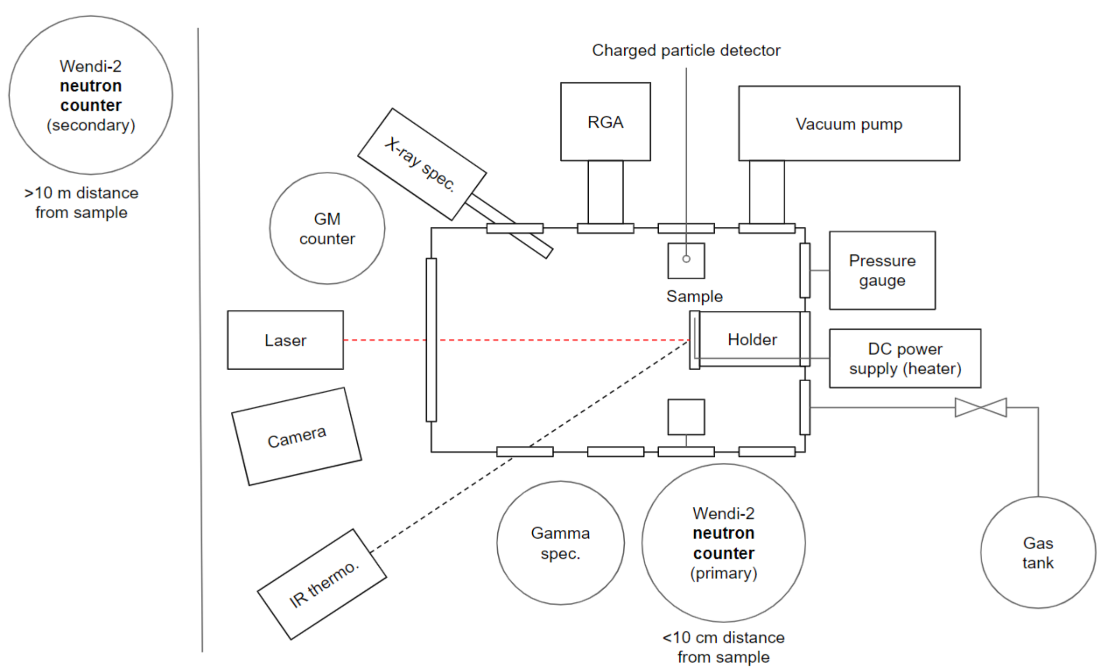

Fig. 4. Proposed experimental platform for prompt detection of LENR nuclear products.

4. Proposed experimental work

An experimental platform as depicted in Fig. 4 enables the study of metal targets with or without laser irradiation under either a high vacuum (10^{-8} Torr) or at a specific pressure (1–10 bar) of H_2, D_2, or Ar. This platform choice enables mimicking the conditions of key historical LENR experiments but with additional diagnostic capabilities.

Connected to and/or surrounding the chamber are: i) a turbopump; ii) a gas manifold capable of providing H_2, D_2, and Ar gas; iii) a residual gas analyzer and wide-range pressure gauge; iv) an IR-thermometer facing the metal target; v) a cryostat/thermostat leading directly to the target; vi) ^{3}He neutron proportional counter tubes with gradient of distance and solid angles relative to the metal foil; vii) two charged particle detectors with equivalent solid-angles relative to the metal foil; viii) a gamma ray spectrometer; ix) a DSLR camera for monitoring the metal foil, x) and laser sources for stimulation of the sample.

The independent variables to be manipulated are: i) the target material (Z_{target} = Pd, Ti); ii) the target temperature (T_{target} = 25–175 °C, $T_{increment}$ = 50 °C; –196–500 °C possibly during Phase 2); iii) the chamber gas (M_{gas} = [vacuum, H_2, D_2, Ar]); iv) the chamber pressure ($P_{chamber}$ = 0.01–4 bar; up to 91 bar possibly during Phase 2); v) the laser wavelength (λ_{laser} = [405, 594, 640, 1064 nm]); the laser type (pulsed or continuous-wave (CW)) vi) the laser strength (E_{laser} up to 1 J/pulse or P_{laser} = 5-50 mW for CW); and spot size (A_{spot} = 0.01–1 cm^2). Note that due to time constraints not all permutations may be tested but primarily those that encompass–and slightly expand–conditions in the referenced experiments. More specifically, focus out to lie on recreating all laser irradiation conditions listed in Table 1-2.

Envisioned data plots: Two distinct iconic plots are proposed to be sought from experimental efforts: First, an x-y plot depicting statistically significant neutron bursts occurring over time, with neutron counts recorded by a primary detector adjacent to the sample, and the neutron background recorded by a secondary detector farther from the sample. Such a plot would be accompanied by statistical analyses as described below, and the neutron bursts would ideally correlate with a manipulated variable (*e.g.*, laser irradiation on-off). Similar iconic plots have been reported[16,24], but without succinct granular detail of the experimental setup, sample characteristics, and conditions for exact replication. Second, a before-and-after SEM-EDX map of a defined 100 × 100 µm grid on the target surface showing the formation of new elemental species, with corroborating TOF-MS and NAA data on the same region showing shifted isotopic distributions compared to a nearby control area.

Control experiments are proposed to include running each attempted replication with/without laser irradiation, and with/without the presence of the chosen gas. Positive results should undergo attempted replication at other sites using the same sample, and samples from the same source material.

There are several prosaic explanations for the observation of purported nuclear ash and/or nuclear product emission that must be accounted for and explicitly ruled out. For nuclear ash, observation of new elements before and after experimentation could be the result of contamination, or simply variability across the target surface that was unaccounted for. We propose to mitigate this potential issue by comprehensive pre- and post-treatment characterization of each sample and by isotopic analysis via TOF-MS and NAA. Since TOF-MS and NAA are destructive, dedicated parts of samples need to be removed for such analyses. For prompt product detection, the focus lies on radiation that is unambiguously nuclear in origin (i.e., neutrons). However, there are prosaic issues with detecting neutrons that must be explicitly addressed, including; i) positive detection events arising from cosmic radiation; ii) false detection events arising from improper signal processing, and iii) false detection events arising from electrical noise. These potential issues can be mitigated by having redundant detectors at smaller solid-angles relative to the target to identify whether detected signals originated from the target.

5. Potential impact and path toward technology development

LENR could have a significant impact on the global energy system. If LENR effects are demonstrated in an irrefutable, reproducible manner, and if such effects can be harnessed and scaled, LENR may overcome prevailing shortcomings of nuclear energy such as the use of radioactive fuels and the production of long-lived waste. The enormous potential of next-generation nuclear energy technology that is clean, safe, and economically competitive is laid out in analyses by McKinsey & Company, IAEA, Breakthrough Institute, and in IEEE[60–63].

However, before the potential impact of LENR can be seriously considered, the existence of purported LENR effects would need to be unequivocally demonstrated in a reproducible manner. Such a "reference experiment" would lead to an influx of financial and human resources needed to properly evaluate potential technological implications of the phenomena. The experimental campaign outlined here seeks to replicate and advance previous LENR studies using state-of-the-art nuclear and material diagnostics. The inspiration for this experimental program comes from theoretical work performed at MIT that has sought to explain the breadth of nuclear products and the poor reproducibility characteristic of LENR reports.

If successful, the project's deliverables may represent a sort of "transistor moment" akin to the 1948 Physical Review Letter by Bardeen & Brattain[64] that put an end to two decades of speculation over the existence or non-existence of purported amplification effects in semiconductor crystals[65]. The evolution of this work may serve as the basis for future simulation and engineering tools that promise new levels of control over nuclear reaction rates and nuclear reaction products–and potentially scalable technology.

Both the burst-like nature of reported neutron emission and the spatially confined sites of morphological and elemental changes suggest that in experiments to date, the conjectured coherent fusion-fission process may have occurred only in a highly constrained manner, at specific sites and specific conditions. In seeking technology development, such conditions would need to be present in a more uniform manner across the sample and across the stimulation period. Given the total number of D pairs present in tested samples (*e.g.*, $\sim 10^{22}$ D pairs in[24]), and bursts corresponding to >1,000 neutrons/min at the source, we can estimate reaction rates of $>10^{-20}$/s per D pair. Other LENR experiments suggest that reaction rates of $>10^{-10}$/s may be possible[66–68]. The latter rate corresponds to energy release on the order of 38 J/s from a 1 cm^3 sample of Pd containing $\sim 10^{23}$ D pairs. If the conjectured coherent fusion-fission reaction can be confirmed and the proposed models can be validated, then LENR systems could be designed from the ground up.

Simulations would allow for tailored lattice composition, structure, and stimulation parameters. Resulting systems could be optimized based on techno-economic metrics such as energy density and cost. This could include substitution of high-cost materials (*e.g.* Pd) with low-cost alternatives (*e.g.* Ni). Fabricating metal-hydride structures with well-defined vacancy content, highly controlled isotopic composition, and predictable responses to dynamic stimulation is within the realm of current capabilities. However, strong experimental results are needed to motivate applied research in this area. The outlined project seeks to lay the foundation for such developments.

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