Muon-catalyzed fusion and annihilation energy generation supersede non-sustainable T+D nuclear fusion

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Abstract

Background: Large-scale fusion reactors using hydrogen isotopes as fuel are still under development at several places in the world. These types of fusion reactors use tritium as fuel for the T +D reaction. However, tritium is not a sustainable fuel to use, since it will require fission reactors for its production, and since it is a dangerous material due to its radioactivity. Thus, fusion relying on tritium fuel should be avoided, and at least two better methods for providing the nuclear energy needed in the world indeed exist already. The first experiments with sustained laser-driven fusion above break-even using deuterium as fuel were published already in 2015.

Results: The well-known muon-induced fusion (also called muon-catalyzed fusion) can use deuterium as fuel. With the recent development of a high intensity (patented) muon source, this method is technically and economically feasible today. The recently developed annihilation energy generation uses ordinary hydrogen as fuel.

Conclusions: muon-induced fusion is able to directly replace most combustion-based power stations in the world, giving sustainable and environmentally harmless power (primarily heat), in this way eliminating most CO_2 emissions of human energy generation origin. Annihilation-based power generation has the potential to replace almost all other uses of fossil fuels within a few decades, also in most mobile applications including spaceflight, where it is the only method which gives relativistic rocket propulsion.

1. Introduction

The experimental and fundamental physics of the quantum material ultra-dense hydrogen H(0) was described in a recent review paper in Physica Scripta) [1]. With experimental interatomic distances of 2.3 ± 0.1 pm in the most commonly observed spin level $s = 2$ (at low pressure and temperature in the laboratory [1, 2]), this is the densest form of matter that exists on Earth and probably also in the Universe (at spin level $s = 1$ of the same density as white dwarf stars). This ultra-dense material has been extensively studied using laser-induced processes like Coulomb explosions (CE), coupled to time-of-flight (TOF) and time-of-flight mass spectrometry (TOF-MS) analysis [2] of its molecular fragments, but also using rotational emission spectroscopy [1, 3, 4]. This spectroscopic method gives a precision of the interatomic distances in the femtometer range. The CE experiments observe molecular fragments with up to 2.5 keV u^{-1} energy [5].

Particles in the MeV range are easily released by nuclear processes in H(0) using < 0.4 J laser pulses [1, 6, 7]. Clear signs of D + D fusion like ^{4}He and ^{3}He ions have been observed [8]. Heat generation from nuclear processes above break-even was also reported in 2015 for the first time ever for D + D fusion in D_2 [9]. The MeV particle signal is so large that it can be measured by a fast oscilloscope (with no pre-amplifiers) directly connected to a metal collector, thus giving undistorted ns-range timing intensity distributions. The decaying signals after the laser pulse agree accurately with kaon (charged and neutral) and charged pion lifetimes [10]. Also muon lifetimes have been confirmed accurately [11]. These fast particles can be observed at distances up to 2 m in a vacuum giving good time resolution [6, 7, 12, 13]. The particle velocity measured by direct timing and by decay dilation corresponds to 10–500 MeV u^{-1} [10, 14, 15]. By using two [9] and three [12] collectors in line, it is found that the fast particles have mass and that they penetrate through mm thick metal with some attenuation and a slight delay. Magnetic deflection studies confirm that many of the initially formed particles are neutral [16] and that the mass of the charged particles is less than 1 u, thus mesons and muons. Measurements with current coils show that many of the particles are charged and relativistic [14, 15, 17]. The generation of muons from the meson decay is confirmed by accurate measurement of the decay-time for the muons [11].

2. Nuclear Energy

Many of the nuclear processes observed in H(0) to give meson ejection take place in small clusters $H_3(0)$ and $H_4(0)$ [18, 17]. The muons formed from the decay of the kaons and pions have kinetic energies > 100 MeV u^{-1} [12, 13, 16]. This means that the processes observed are not ordinary D + D fusion processes, even if ordinary fusion processes also exist in this system [8]. The theory at present is that two baryons with six quarks recombine to form three light mesons (kaons and pions), each with two quarks [19–22]. Such a process is energetically possible and gives a large excess kinetic energy to the particles formed. Most of the reaction steps deduced [23] agree with the standard model of particle physics. From the experiments, it is also clear that both kaons and pions can also be formed initially with low kinetic energy [10] by pair production from the excess nuclear energy.

For the future of energy generation, fission processes using U or Th are believed to soon be phased out, not only due to considerable risks for accidents with their operation (for example, the Three-Mile Island, Chernobyl and Fukushima reactor accidents) but also due to the problems with large volumes of radioactive waste products and the costs and risks associated with the storage of radioactive waste for many thousand years. On the other hand, fusion processes based on T + D fusion reactions in the form of magnetic confinement (like the Iter research facility and other tokamaks) have attracted large interest and large government funding around the world. The possibility of technological and commercial success in these cases can still not be estimated reliably. Also laser-induced ICF (inertial confinement fusion) setups like the world´s largest laser (the National Ignition Facility (NIF) at Lawrence Livermore, California, USA) has required large investments, so far without much success [24, 25]. (However, this facility may anyway have been built mainly for weapons research.) Besides all the technical and scientific problems surrounding these two main trends in using fusion power, there are more basic problems related to their fuel which make these large-scale methods non-sustainable. Both these future methods are intended to use T + D fusion, since this is the only hydrogen fusion reaction that can work under the conditions attainable in such reactors, since it has the lowest ignition temperature. For example D + D fusion cannot be used. However, the fuel T does not exist in nature, and it will probably need to be produced in fission (uranium) reactors and be transported to the fusion reactor sites. This means that these fusion methods are not more sustainable than fission. The other problem with tritium is that it is radioactive and accidents with leakage to the atmosphere are likely to take place. In fact, the large-scale use of tritium is questionable since tritium is a radioactive gas that is difficult to measure. Leakage of tritium to the atmosphere will give enhanced radioactivity in breathing air, finally in the form of water which is easily absorbed in lungs and which gives radioactive damage and risk for lung cancer. (As given in various safety data sheats SDS: GHS Signal Word: Danger. Exposure Routes: ingestion, inhalation, puncture, wound, skin contamination absorption). It should be observed that tritium emits beta radiation (electrons) with quite low energy, maximum of 18.6 keV. This means that it cannot be detected by standard radiation instruments like Geiger counters (GM tubes), due to the windows necessary in such devices. Thus, it is not easy to detect a leakage of tritium to air from any type of device. Ordinary undamaged skin is stated to not be penetrated by the beta radiation from tritium [26]. No such obstacles exist in the lungs, so the tissue in lungs will be damaged by this beta radiation.

Another problem is of course the risk of explosive processes in the fusion reactor. Plasma based methods have such risks, since the fusion process is thermonuclear and may support itself in an ignited mode. Other methods of fusion which do not use plasmas (like muon-induced fusion) cannot give any explosive processes.

Thus, it is obvious that a sustainable nuclear fusion process must use deuterium or protium as hydrogen fuels, or possibly other more complex processes based on boron or lithium [27]. Even if this is not yet generally known, suitable sustainable hydrogen nuclear reaction methods do exist. We will describe and discuss two of them below under the headings 2a. muon-induced fusion and 2b. annihilation. One aspect which is of interest is the efficiency of the nuclear process, which may be characterized by the fraction of the fuel mass which is converted to energy. Such data are given in Table 1. It is there seen that D + D fusion by muon catalyzed (induced) fusion should be the primary choice of a sustainable fusion process at present. This is probably the first and also only generation of fusion reactors which needs to exist, since the next generation of nuclear power generation after that is likely to be annihilation power using ordinary hydrogen as fuel.

2a. Muon-induced fusion

The central reactions in muon-induced fusion in D_2 gas with energy out given are [14, 28]

$Dde^+ + \mu^- \rightarrow dd\mu^+ + e^-$ (1)

$dd\mu^+ \rightarrow {}^3He^{2+} + n + \mu^-$ 3.3 MeV (2)

$dd\mu^+ \rightarrow {}^3He\mu^+ + n$ 3.3 MeV (2a)

$dd\mu^+ \rightarrow T^+ + p^+ + \mu^-$ 4.0 MeV (3)

$dd\mu^+ \rightarrow T\mu + p^+$ 4.0 MeV (3a)

Reaction (1) is the step where the muon replaces the electron in the D_2^+ ion inside a D_2 molecule. This gives a shorter d-d bond distance in approximate proportion to the ratio of the masses of the muon and the electron, thus 105.7 MeV/0.511 MeV = 207 times shorter distance. Thus, instead of the interatomic distance of 106 pm in normal D_2^+, the d-d distance in $(dd\mu)^+$ is expected to be 0.51 pm. In reactions (2) and (3), the muons are released after the dd fusion which means that the muons can take part in several such reactions Eq. (1) before they decay with lifetime 2.20 μs. This feature is the reason for the name muon-catalyzed fusion, and the number of steps possible has been an important point for research and discussion since the first observations of muon-induced fusion in 1957 [29]. However, with the recent development of intense muon generators giving cheap muons [30] this point is no longer of great concern. The muon-induced and muon-catalyzed fusion processes have been studied by large groups since 1957 with impressive results [28, 31, 32]. Reactors of this type were recently analyzed carefully in a Ph.D thesis in London 2018 [33] by R.S. Kelly. The energetics of the nuclear reactions using the existing muon generator have been summarized [14]. The function of the muon generator was proved further by the observation of neutrons from fusion in D_2 gas [34]. More extensive studies on similar themes will soon be published by scientists in this field working in Oslo and Reykjavik.

One important aspect of the muon-induced fusion process is that it can use deuterium as fuel. As seen in reaction (3) this fusion process gives tritium as one product. Tritium can then fuse with deuterium by the muon-induced process, giving a more energetic reaction step [14]. This means that the composition of the fuel in the reactor and thus also the energy output changes with time, increasing when the fuel becomes richer in tritium [14, 33]. This increase in tritium takes years of running the muon-induced reactor. This tritium does not need to be handled openly, and the risk of leakage to the atmosphere is rather small and means not less than a catastrophic failure of the high-pressure deuterium-tritium reactor. It is envisaged that the central reactor container is exchanged when the high-pressure vessel needs service or similar or that the gas in the reactor is exchanged to lower tritium content after a period of several years, when the tritium content has increased. In this way, an environmentally safer way of production of tritium exists, cutting the ties from fusion to fission reactors and thus making them obsolete even if large-scale fusion has been developed and fills a demand for example for large-scale electricity generation.

In the same way, it is also possible to produce deuterium from protium in a muon-induced fusion reactor. However, this reaction is probably too slow to useful [14, 31, 32].This may mean that ordinary hydrogen is indeed possible to use as a fuel and starting material for fusion fuel production using muon-induced fusion, not only in the annihilation energy generation process described below.

2b. Annihilation

The most important property of a nuclear process for energy generation is of course that it is possible to reach break-even, thus that more energy can be generated by the process than what is required to start and maintain it. The first such report on break-even in fusion was published in 2015 [9] in a system using ultra-dense deuterium D(0) as fuel. (The so called scientific break-even in NIF [24] is a special definition of break-even which is not of practical interest). The process observed in D(0) [9] was mixed as can be concluded now, using both muon-induced fusion and annihilation energy generation. At the time of the experiment, the annihilation process had not yet been identified, so the process was thought to be laser-induced ICF using the D + D reaction.

The annihilation process generates fast mesons, mainly charged and neutral kaons at typical energies of 200 MeV or 400 MeV u^{-1} [10, 15, 35]. From this high energy, it is estimated that 200–600 MeV is generated per pair of nucleons, thus 10–30% of the nucleon mass is converted to kinetic energy. The mass of the kaons is also transferred to lighter particles and kinetic energy by the kaon and pion decays, but this energy is partly lost to neutrinos and gammas. Overall, it is estimated that up to 50% of the mass of the initially reacting nucleon pair is converted to useful energy. A conservative estimate is used in Table 1 as 10–50% to thermal or kinetic energy. Since the technology for transfer to kinetic energy is not yet developed, this value is just an estimate. The first description of a rocket drive for relativistic interstellar travel was recently published [35], using the momentum of the kaons from the annihilation process for the rocket drive. This is a first step in the development of new technology to utilize the annihilation energy process.

As an example of the general results on mesons, a simple decaying signal from laser-induced annihilation in D(0) is shown in Fig. 1. The results agree well with the decay of stationary charged pions [19–22]. Pairs of pions are often found to be formed together with the kaons with much lower kinetic energy than the kaons. This means that there is no time dilation for the pions and their observed lifetime agrees with standard values [22], in this case within 0.4%. In this experiment, a pair of magnets was used to deflect and separate the particles with different charge, and the difference between the two deflected fluxes was measured including their sign. In this way, the signal due to neutral kaons was suppressed, which otherwise often is the largest signal in the meson experiments. The lightest and slowest mesons thus the charged pions should be the easiest magnetically separated particles, as found. The good agreement with the accepted decay time for pions $\pi^{\pm}$ proves that high energies and large particle masses exist in the laser-induced annihilation process. Results on charged and neutral kaons are also found in other references [12–14, 16, 17].

Declarations

Ethical Approval and Consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of supporting data

All data are available or cited in the paper.

Competing interests

The author is owner in a company that works with development of muon catalyzed fusion, but there are no competing interests since the sustainability problems of different fusion methods are well known.

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Authors' contributions

LH has contributed alone to all aspects of the paper.

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Tables

Table 1. Characteristics of different hydrogen-based nuclear reactions for energy production.

Est. means estimated. ….. means that the fuel composition changes over time in a closed reactor.

Fuel reaction	Method	Reactor type	Power Range (thermal or electricity)	efficiency (%)	Sustained over-break-even operation demonstrated	Commercial start
T + D	Plasma	Magnetic or inertial confinement	GW?	18/4500 = 0.3%	──	Much later than 2030?
T + D	Muon catalyzed fusion	Tube reactor	MW_{th}	18/4500 = 0.3%	──	2021
D+D…..T+D	Muon catalyzed fusion	Tube reactor	15 kW_{th}… MW_{th}	4/3600 = 0.1%…..	soon	2021
D+D	Annihilation	Plane reactor	200kW_{th}-MW	10-50% estimated	2015	2025
D+D	Plasma	Magnetic or inertial confinement	-	4/3600 = 0.1… %		Never?
p+D… D+D	Muon catalyzed fusion	Tube reactor	<<20 kW_{th}?	5.5/2700 = 0.2%		Never?
p+p	Annihilation	Plane reactor	200kW_{th}-MW	10-50% est.		2025 est.
p+p, D+D	Annihilation	mechanical	kW_{el}-MW_{el}	10-50% est.		2030 est.

Figures

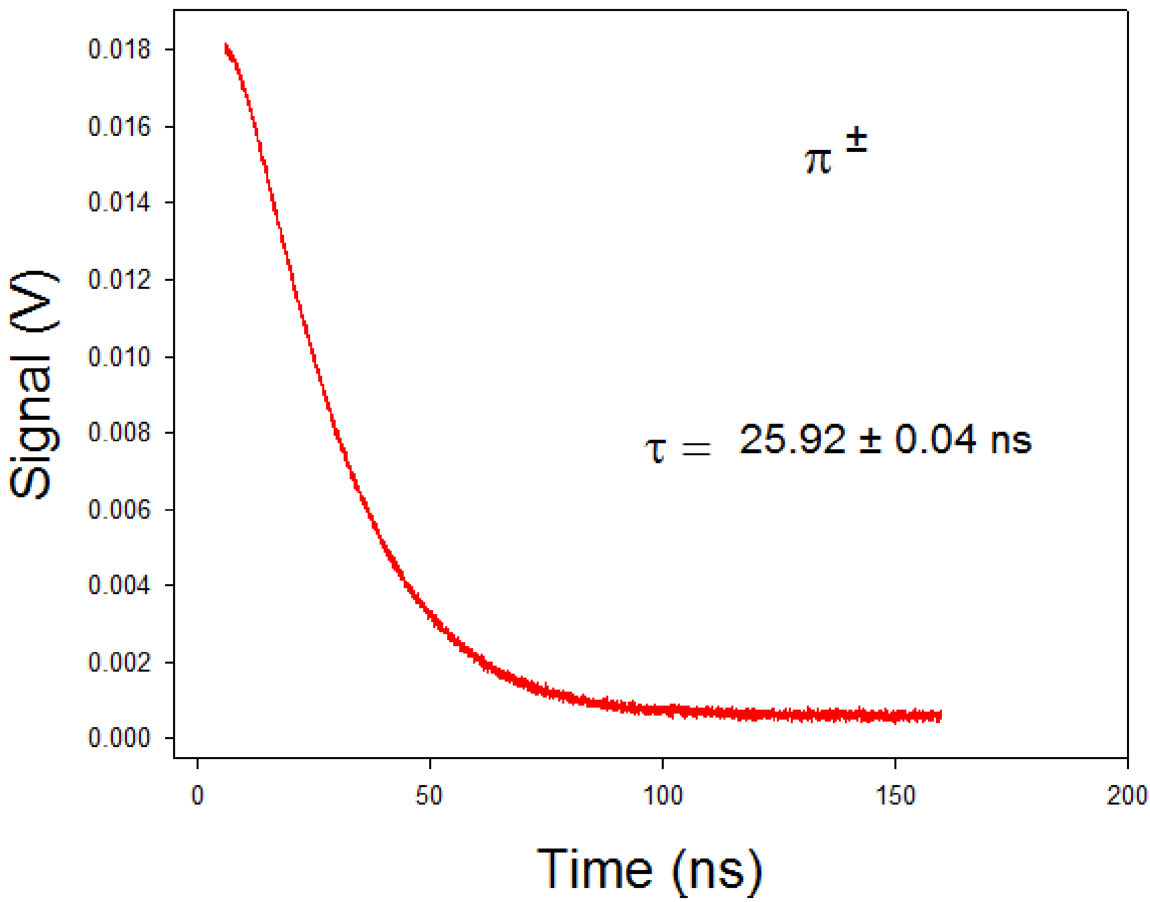

Figure 1

Time variation of meson signal from an annihilation experiment. D(0) on laser target, 50 mbar D2 gas in 2 m long tubular vertical chamber. The decay time is obtained by a converged non-linear least sqares 2-parameter fit in the program SigmaPlot 14 using 560 measured points for the fit. The time constant value found agrees within 0.4% with the accepted decay time for a stationary charged pion, at 26.033 ns [22].