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Future interstellar rockets may use laser-induced annihilation reactions for relativistic drive

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ABSTRACT

Interstellar probes and future interstellar travel will require relativistic rockets. The problem is that such a rocket drive requires that the rocket exhaust velocity from the fuel also is relativistic, since otherwise the rocket thrust is much too small: the total mass of the fuel will be so large that relativistic speeds cannot be reached in a reasonable time and the total mass of the rocket will be extremely large. Until now, no technology was known that would be able to give rocket exhaust at relativistic speed and a high enough momentum for relativistic travel. Here, a useful method for relativistic interstellar propulsion is described for the first time. This method gives exhaust at relativistic speeds and is a factor of at least one hundred better than normal fusion due to its increased energy output from the annihilation-like meson formation processes. It uses ordinary hydrogen as fuel so a return travel is possible after refuelling almost anywhere in space. The central nuclear processes have been studied in around 20 publications, which is considered to be sufficient evidence for the general properties. The nuclear processes give relativistic particles (kaons, pions and muons) by laser-induced annihilation-like processes in ultra-dense hydrogen H(0). The kinetic energy of the mesons is 1300 times larger than the energy of the laser pulse. This method is superior to the laser-sail method by several orders of magnitude and is suitable for large spaceships.

1. Introduction

Interstellar probes and future interstellar travel will require relativistic rockets, with a slightly arbitrary definition of relativistic meaning rockets moving at velocities above 50% of the velocity of light or $> 0.5\,c$. Such a rocket requires that the exhaust velocity from the fuel also is relativistic, since otherwise the rocket thrust is much too small. Thus, mankind can never expect to be able to probe or travel in interstellar space if relativistic rockets are not developed. So far, no technology is known that would be able to give high enough energy and a rocket exhaust at relativistic speed and high enough momentum for relativistic travel.

The possible theoretical principles for relativistic rocket drives are however understood and discussed [1] in terms of photon ejection or nucleon annihilation reactions. A few other relevant studies of this type exist [2,3]. So the problem is to find a method which can use an annihilation-like process without a clumsy and costly brute-force method of creating antimatter for example by accelerator-based methods which will be extremely energy inefficient and will require complex methods for storage of the antimatter [2].

This problem has now been solved not only in theory. For the first time a feasible method for relativistic interstellar propulsion is described in detail. It is a at least one hundred times better than ordinary nuclear fusion which is often considered to be the energy generation method to use for interstellar travel. Further, it uses ordinary hydrogen as fuel so a return travel is possible after refuelling almost anywhere in space. No other rocket drive has solved this problem with refuelling. This annihilation-*like* method is well studied in the laboratory and gives initially fast kaons and pions from protons or deuterons by annihilation-like processes. We use the phrase annihilation-*like* since the practical evidence and use is more important for its characterization than the claim inherent in the strict nomenclature without the *-like*. The necessary antimatter used is concluded to be formed by oscillations of the quasi-neutrons [4,5] initially formed in the ultra-dense hydrogen by laser-induced processes from spin state $s = 2$ to $s = 1$ [4]. Considerable progress in the understanding of these complex nuclear processes has been made already [6]. Thus, a practical solution exists for the annihilation rocket drive, ejecting relativistic massive particles and not only photons [2,3].

It is appropriate to now also compare this laser-based method with

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other possible rocket drives using lasers. One propulsion method using stationary lasers and laser sails on interstellar space probes has been studied [7,8] and some other laser-based methods appear feasible and will thus be mentioned here. In the method with laser-sails the momentum transfer is due to the photons reflecting off the sails. For comparison, the lasers employed for the annihilation-drive described here have pulse energy of < 0.5 J. This means that the total impulse per laser shot with 10^{18} photons is of the order of 10^{-9} Js. Laser-ablation methods can probably not give higher impulse than the laser pulse, since the velocities of the sputtered particles are caused by the photon impact.

In the annihilation method described here, each laser pulse gives of the order of 10^{13} mesons [5] with relativistic velocity. This gives an impulse which is up to 3000 times larger than the photon impulse. Thus, this annihilation-like method is far superior over other laser-based space propulsion methods.

2. Rocket propulsion

The treatment here is neither exhaustive nor quantitative, but is only intended to give the most basic conclusions concerning rockets for interstellar travel. The so called rocket equation (Tsiolkovsky rocket equation) can be given as

$$v_f - v_0 = u \ln(m_0/m_f) \tag{1}$$

with v_f the final velocity from the initial velocity v_0, given by a mass ejection at exhaust velocity u, with rocket mass starting at mass m_0 and ending at mass m_f. This equation is not accurate for relativistic velocities, but it provides a simple and useful description of the required quantities for an examination of the general rocket properties. The relativistic form of Eq. (1) is given for example in Ref. [3]. With an exhaust velocity of 10^{-2} c or 3×10^6 m s^{-1} the final rocket velocity in Eq. (1) becomes 6.9×10^6 m s^{-1} after ejecting 90% of its mass. This relation between exhaust velocity and rocket velocity is typical but with decreasing final velocity towards higher velocities due to relativistic effects. Thus, for travel forth and back without re-fuelling, the ejected mass needs to be 99% to reach a velocity in both directions which is somewhat larger than the exhaust velocity. A rocket structure with a so called dry mass m_f of only 1% as required for this is of course an engineering challenge and can only be built in space.

Fusion processes are often believed to be useful for future interstellar rockets, especially in popular culture. However, the energy given to the particles ejected by a fusion process is rather small, in the first step in D + D fusion only around 3 MeV u^{-1}. This corresponds to only 0.08 c, thus far from relativistic which may be considered to be 0.5 c as suggested above. Even with T + D fusion, the highest energy is only 14 MeV u^{-1}, thus only 0.17 c. This is the maximum velocity that can be expected from nuclear fusion using hydrogen isotopes. This indicates a final velocity from D + D fusion of 5.5×10^7 m s^{-1} or close to 0.2 c without including any relativistic effects which will give slightly lower velocity. However, just a small part of the total D mass is converted to fast particles moving in the wanted exhaust direction, so far from 90% of the mass is exhausted as wanted. If T + D fusion is used, the final velocity in the same way becomes 1.2×10^8 m s^{-1} or 0.4 c. This velocity is still not sufficient. Besides, the problems with using T as fuel are enormous, especially for space travel, since this fuel must be produced from Li by reactions with neutrons [9,10] for example in fission reactors. Thus, nuclear fusion using the D + D or T + D reactions cannot give relativistic rockets.

3. Laser-induced annihilation

The lowest state of so-called Rydberg Matter in excitation state $n = 1$ can only be formed from hydrogen atoms and is designated H(1) [4]. This is dense or metallic hydrogen. The bond distance is 153 pm or 2.9 times the Bohr radius. It has a density of approximately 0.5 kg dm^{-3}. A much denser state exists for hydrogen, named H(0) or ultra-dense hydrogen [4]. With a normal internuclear distance of 2.3 pm, its density is extremely large, > 130 kg cm^{-3}. Nuclear processes can easily be induced in H(0) by pulsed lasers. With the detection of laser-induced nuclear processes in ultra-dense hydrogen H(0) [4,11] in our laboratory, an exhaust process giving ejected particles at relativistic velocities has been found [4,12,13]. The particles ejected are similar to those found in nucleon-antinucleon annihilation [14], so the processes observed are not nuclear fusion (as was thought initially) but a form of particle annihilation. The initial particles formed are observed in the laboratory studies [4,12,13,15]. The particles formed are both charged and neutral kaons with a mass close to 0.5 mass units (495 MeV). The most long-lived kaons decay with a time constant of 52 ns to pions and muons which are lighter and faster [16,17].

This means that relativistic rockets may be developed on this base. The fuel is ordinary hydrogen or more precisely protium in ultra-dense form H(0) [4]: this means that a return travel can also be expected at relativistic velocity since hydrogen is the most abundant element in space and can be used for re-fuelling at any suitable point during the travel. It is even likely that space contains large amounts of ultra-dense hydrogen [18–20].

From the spectrum of particles ejected, the approximate annihilation process is suggested to be [13]

$$\mathrm{p} + \mathrm{p} \rightarrow \mathrm{K}^+ + \mathrm{K}^- + \mathrm{K}^0_L \tag{2}$$

The two protons have a total mass of 1.88 GeV while the three kaon products have total mass of 1.49 GeV. Thus 390 MeV is given to the kaons, or 130 MeV per kaon on average equal to 250 MeV u^{-1}. This corresponds to 0.61 c on average, including relativistic effects. This velocity is a factor of seven higher than for D + D fusion. The most common decay of the charged kaons gives a muon and a muon neutrino, with excess energy of 387 MeV. This gives an average energy of 194 MeV to the muon or a velocity of 0.94 c. On average, each proton gives several particles with velocities close to c. In this way, rocket velocities relatively close to c should be reached. The principle of the system is shown in Fig. 1. The ultra-dense hydrogen H(0) is produced in the catalyst from the hydrogen gas feed [4]. The target support for H(0) may be metal or metal oxide [21]. For most of the studies in the laboratory a standard Q-switched pulsed Nd:YAG laser with 10 Hz pulse repetition rate at 1064 nm and with 5–7 ns long pulses has been used, with pulse energies as low as 0.1–0.5 J. Other similar lasers like Nd:glass may have better thermal properties. Solid-state photodiode pumping will give long lifetime for such lasers. Each laser pulse in the

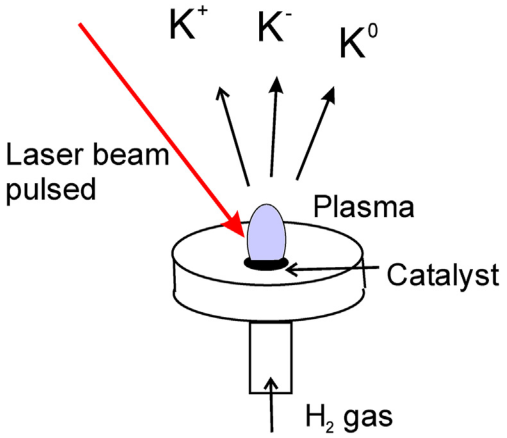

Fig. 1. Outline of a laser-induced annihilation generator for space propulsion. The laser is for example a Q-switched Nd type laser with pulse energy as low as 0.1–0.4 J [11,12]. The catalyst is a hydrogen transfer catalyst [28–31]. For a more optimized target construction for generating larger amounts of H(0), see the recent patent description [22].

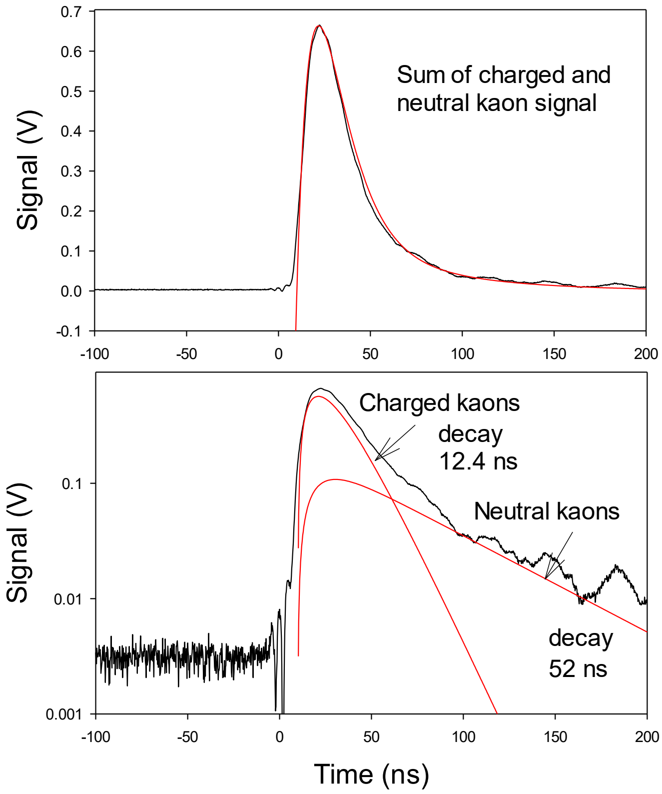

Fig. 2. Decay of kaon signal from an annihilation generator after the laser pulse, with hydrogen pressure 0.6 mbar in the apparatus. Same signal in linear plot (top panel) and log plot (bottom panel). The detector for the fast particles is a small, 20 μm thick aluminum foil at approximately 1 m distance used as emitter of secondary electrons which are released from it by the fast muons reaching the foil. The muons are formed by decay of the kaons outside the target. This decay gives the decaying muon-secondary electron signal with correct kaon decay times (or slightly longer due to relativistic effects). Charged kaons $K^{\pm}$ have decay time 12.4 ns at rest while long-lived neutral kaons K_L^0 have decay time 52 ns at rest. The secondary electron signal from the aluminum foil is measured directly by a 300 MHz oscilloscope with 50 Ohms input (no amplifiers used). The peak of the signal is thus seen to be 12 mA = 0.6 V. The number of charges in the pulse signal generated at the small distant foil is 10^9 per laser pulse.

laboratory studies gives of the order of 10^{13} mesons [5]. The formation of large numbers of muons in the processes after meson decay is used in a patented muon generator intended for muon-catalyzed fusion reactors [5,22]. The correct decay time for the generated muons has been verified [23]. Correct decay-times with an accuracy of 1% relative to accepted values are also measured for charged pions [6].

It is not yet known exactly how large fraction of the proton mass that is converted to useful kinetic energy, since the decay processes are quite complex [16,17]. Most kaon, pion and muon decay processes form one or two neutrinos which give very little momentum transfer and which thus can be considered to be lost [16,17]. The final particle decay products are electrons and positrons, each with a mass of only 511 keV. They may annihilate each other to some extent, giving gamma photons [16,17]. Some meson decay channels of lower probability also end up as gamma photons. Since the spectrum of kaons and other particles formed varies with the conditions for H(0) in the experiments, an exact calculation is not yet possible or meaningful. One experimental result with mainly charged kaon ejection is shown in Fig. 2, of the same type as described in Ref. [4,12,13]. This experiment is described further in the figure caption. It is the exponential slope which gives the lifetimes of the mesons, in this case of the kaons, as demonstrated in Fig. 2. Extensive results on this have already been published [4,5,12,13,23,24]. Further results were also submitted recently [6] with an accuracy of 1% relative to the accepted pion life-time. The same meson beam signals as in Fig. 2 have also been measured with a ferrite core coil (current transformer), Passivated Implanted Planar Silicon Detectors (PIPS detectors) and Galileo channeltron detector which proves that the signal is due to charged particles and not to photons or neutrinos ([6,22–24] and submitted).

Particles from the plasma or from other processes than the annihilation are much slower than the mesons and muons, outside the time range shown. They are further not easily observed in the experiments due to their much lower energy, giving only a few secondary electrons at the collector-detector foil. The laser target with ultra-dense hydrogen used in this case is of the form fully described in a recent patent [22]. A reasonable estimate is that 50% of the total initial mass of the protons is lost to neutrinos and photons. Some of the momentum of the photons may however also be useful for the rocket drive. Thus, it is estimated that 50% of the proton mass is converted to useful kinetic energy by such a rocket drive. The total energy from these nuclear processes is roughly a factor of hundred higher than from fusion, so the hydrogen fuel lasts much longer than if fusion was used for the drive. Also, ordinary hydrogen can be used as fuel for the annihilation process, which would not be possible if fusion was the main drive process used.

This is the only realistic scheme for driving a relativistic rocket known so far, including both the energy release and massive particle ejection. Of course, the same annihilation-like energy source may be used to give mainly photons [2,3] if an efficient process for this can be found.

Technical problems of course exist:

1) Many of the particles formed can penetrate far through normal materials, thus an equal number of particles may be ejected in all directions giving no directed thrust. The simple inherent solution to this is to see to that thick layers of ultra-dense hydrogen are formed on the target which prevents the penetration by reflecting the mesons from these layers. This effect was studied for ions in Refs. [25].
2) The temperature of the local plasma formed may by higher than 100 MK due to the large density of fast particles created [16,17]. The x-rays and gamma-photons formed must be shielded from reaching electronic equipment and living organisms.
3) The lasers used for the annihilation drive need to be highly reliable. Nd:YAG lasers have been used successfully for the numerous published experiments [4,12,13,15,26], and with diodes instead of the flash lamps (used for these studies) their reliability and efficiency will probably be very good.

Great benefits also exist:

1) Few neutrons are formed [27], contrary to ordinary hydrogen fusion. Thus the risks of damage to living organisms by neutrons or even by induced radioactivity is much lower than with ordinary fusion. The lifetime of mesons is much shorter than for neutrons (< 52 ns for mesons and 15 min for neutrons) which means a much smaller volume with strong radiation around the present drive relatively to a fusion drive.
2) Ordinary hydrogen is used as fuel, and there is no need for using tritium. Hydrogen fuel exists at varying densities everywhere in space, and it is collectable and useable for the propulsion even if it is not initially in ultra-dense form.
3) The catalysts needed for producing the ultra-dense hydrogen H(0) from hydrogen gas are made of base metals like iron and chromium [28,29] in oxidized form with alkali metal (for example potassium) as promoter [30]. These materials should be available in most star systems on asteroids and small planets with solid surfaces with a close example of Mars (the red iron oxide planet), if the catalyst becomes contaminated, or deactivated [31] for other reasons, and has to be replaced.

4. Specific properties of H(0)

The physics of ultradense hydrogen H(0) was recently described in a review paper [4], which summarized the results from 40 published papers. H(0) is the first superfluid and superconductive material stable far above room temperature, but its super properties (thin layers which creep over surfaces and through openings) mean that it is not so easy to collect and store even if it is stable below a temperature of 1 MK [20]. H (0) forms a thin layer on the carrier material, and has the same temperature as the carrier [24]. The pressure in this film is difficult to measure. The super state of H(0) is one state out of several between which the material changes spontaneously [4]. The most suitable future storage medium will probably be an assembly of thin metallic or graphitic films. H(0) can be stored most easily at temperatures of a few hundred K, and at pressures from zero to a few bars. Since H(0) is easily produced from hydrogen gas in contact with a suitable catalyst [29,30], it will best be produced in the laser drives in the rockets when needed. Large-scale storage as H(0) is not recommended since the spontaneous nuclear reactions taking place in H(0) [32] could give uncontrolled energy and radiation release. For further descriptions of the complex properties of H(0), please see the review paper [4] and the original studies cited there.

5. Efficiency

The efficiency of the drive is here evaluated in terms of energy. This is not the complete picture, but it should suffice for the description of the principle of this new concept for propulsion in space.

Each laser pulse in the laboratory experiments contains 10^{18} photons each with an energy of around 1 eV. The laser pulse releases up to 10^{13} mesons from the annihilation process, each of the three kaons with an average kinetic energy of 130 MeV as described above. This corresponds to an efficiency of $130 \times 10^{19}/1 \times 10^{18} = 1300$ thus 1300 times higher energy as output, of course only including the kinetic energy of the mesons.

The power necessary for running a diode pumped Nd laser is estimated to be 100 W, while the power in the laser pulses is of the order of 1–5 W (0.1–0.5 J at 10 Hz) giving 1300 times higher kinetic energy for the mesons as found above, or 1300 times higher power at 1.3–6.5 kW. Thus, the power for running the laser is negligible.

The annihilation process is initiated by the transfer of H–H pairs in small H(0) clusters $H_3(0)$ and $H_4(0)$ [24] from spin state $s = 2$ to $s = 1$ [4]. Not all photons in the laser pulse will interact with such pairs in small clusters, since H(0) is mainly in the form of chain clusters $H_{2N}(0)$ at various s levels [4]. This is the reason why the laser pulse with 10^{18} photons gives (only) 10^{13} mesons. This is anyway the highest rate and density of meson formation ever attained.

6. Conclusions

A method of reaching relativistic exhaust velocities in a spaceship useful for interstellar travel is described. It is based on the well-studied laser-induced annihilation-like nuclear processes in ultra-dense hydrogen H(0) in which both neutral and charged kaons are formed with kinetic energy above 100 MeV for each particle. A complete description of the nuclear processes giving the mesons was recently submitted. The fuel for this drive is ordinary hydrogen, which means that refuelling is possible during interstellar travel, ensuring return travel. Modern Nd lasers have good properties for this type of drive. The system needed for the drive has low complexity. The energy efficiency is more than a factor of 1000. thus > 1000 times more kinetic energy is given to the mesons formed relative to the energy in the laser pulse. Experimental reactors which produce relativistic particles from annihilation are operating in Sweden, Norway and Iceland and a propulsion system for relativistic drive should be feasible within a decade.

Declaration of competing interest

The authors of the manuscript "Future interstellar rockets may use laser-induced annihilation reactions for relativistic drive", Leif Holmlid and Sindre Zeiner-Gundersen declare no conflict of interest.

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