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Muon-Boosted Fusion Propulsion System

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[Abstract] Several years ago a great deal of excitement was generated by muon-catalyzed fusion due to the experimentally verified multiplicity – 100 per muon – of fusion reactions in deuterium (D) and tritium (T) resulting from this process. This excitement was somewhat tempered, however, in its application to power-producing reactors due to the large amounts of energy expended in the production of muons and the need for the presence of muon-producing accelerators in the proximity of the fusion reactor. It was found that the combination of these factors rendered the power balance for the system unfavorable. These problems can now be significantly alleviated by utilizing the pions that are generated by the "at rest" annihilation of antiprotons in U^{238} targets. Upon decay, these pions give rise to the muons needed to catalyze DT fusion reactions, and prior to their decay they, along with the fission fragments, can contribute to additional fusion reactions through the plasma heating they provide. Catalysis takes place because a negative muon, when slowing down, forms a meso atom with tritium, and during a certain time this meso atom collides with a deuterium to form a mesomolecular ion. It takes a very short time, subsequently, for an exothermic fusion reaction to take place. It can be shown that the number of cycles which a muon has time to catalyze is about 100, i.e. a single muon can give rise, during its lifetime, to a hundred fusion reactions releasing about 2 GeV of energy. We apply this to a fusion propulsion system consisting of a Gasdynamic Mirror (GDM) attached to an antiproton trap where "at rest" annihilation of antiprotons on U^{238} targets is employed for driving the system. We find for a mission of interest, such as a Mars mission, the number of antiprotons required to achieve the mission is substantially reduced due to muon catalysis.

Nomenclature

β = ratio of plasma pressure to vacuum magnetic field pressure
L = plasma length
λ = collision mean free path
n = electron density
R = plasma mirror ratio
R_0 = vacuum mirror ratio
T = electron temperature
τ_0 = muon life time
τ_c = plasma confinement time
τ_f = deuterium-tritium fusion time
v_{th} = ion thermal velocity
w_c = muon recycle probability
w_s = muon capture probability
x_c = number of cycles

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I. Introductory Remarks

THE idea that negative muons (μ^-) might be able to catalyze proton-deuterium (p-D) fusion was first considered by Frank[1] in 1947, and it has been seen experimentally in 1956 by Alvarez *et al.*[2] Deuterium-tritium (DT) fusion catalyzed by muons was discussed by Sakharov and Zeldovich[3], and in 1957 Jackson[4] reconsidered these possibilities and concluded that the DT interaction has the highest probability.

Many of the problems often noted with the muon catalyzed fusion approach including the positioning of a pion-muon producing accelerator in the proximity of the fusion reactor can be readily alleviated using a recent approach to the production of these particles. This approach is based on theoretical and experimental studies[5,6] that showed that "at rest" annihilation of antiprotons in the uranium isotope U^{238} leads to fission at nearly 100% efficiency. When an antiproton or a proton with multiple MeV kinetic energy slams into a target material, it undergoes collisions with the electrons of the target and slows down by giving up energy to these particles. In the case of the proton, it comes to rest in the material and forms a chemical bond with other atoms or diffuses around as atomic hydrogen. In the case of the antiproton, it displaces an orbital electron around the nucleus and begins immediately to cascade down in energy towards the ground state emitting x-rays as it makes these transitions. Eventually the orbital state overlaps with the "wave function" of the nucleus and annihilation with either a neutron or a proton in the nucleus takes place. At this point the kinetic energy of the antiproton is measured in eV's, and not in MeV's, hence the label "at rest" annihilation. Nuclear fission following the at rest annihilation of antiprotons in heavy nuclei has been demonstrated in uranium and bismuth among others, and measurements have been made of the mass distribution of the fission fragments, as well as the multiplicity of the charged particles that were emitted in the process. It was shown, for example[7], that in the case of uranium the average masses and kinetic energies of the fission fragments are 212 amu and 160 MeV, respectively. In addition to the fission fragments, the annihilation products, namely the pions, are also ejected in addition to about 20 high energy neutrons. Pion production by the $\overline{p}-p$ annihilation process proceeds in accordance with the reaction

$$\overline{p}+p\rightarrow a\pi^0+b\pi^++b\pi^- \tag{1}$$

where the neutral pion π^0 decays into 2 gamma rays almost instantly (8.4×10^{-18} seconds), and the positively charged pion π^+ and the negatively charged pion π^- (along with π^0) are produced with a distribution given by $a\approx 2$, $b\approx 1.5$. Furthermore, the charged pions decay schemes are given by

$$\pi^+\xrightarrow{72ns}\mu^++\nu_\mu \tag{2}$$

$$\pi^-\xrightarrow{72ns}\mu^-+\overline{\nu}_\mu \tag{3}$$

where μ^+ and μ^- are respectively the positively and negatively charged muons, and ν_μ and $\overline{\nu}_\mu$ are respectively the muon neutrino and muon antineutrino. We observe that the decay times for the pions are 72 nanoseconds while those of the muons, namely

$$\mu^+\xrightarrow{6.2\mu s}e^-+\nu_\mu+\overline{\nu}_e \tag{4}$$

$$\mu^-\xrightarrow{6.2\mu s}e^++\overline{\nu}_\mu+\nu_e \tag{5}$$

are much longer, i.e. about 6 microseconds. This fact is especially relevant not only for the muon-catalyzed fusion utilizing the μ^-'s, but also for potential heating of the plasma by these charged particles where kinetic energies at birth are 250 MeV for the pions and 192.3 MeV for the muons.

Muon catalysis in a DT gas proceeds as illustrated in Fig. 1. When slowing down, a negative muon (μ^-) forms the meso atoms ($D\mu^-$) or ($T\mu^-$) with probabilities c and $(1-c)$, which are proportional to the relative concentration of deuterium and tritium in the D-T mixture. During the time τ_{DT} the muon is transferred from deuterium to tritium. During the time $\tau_{DT\mu}$ a meso atom ($T\mu^-$) collides with deuterium and forms a mesomolecular

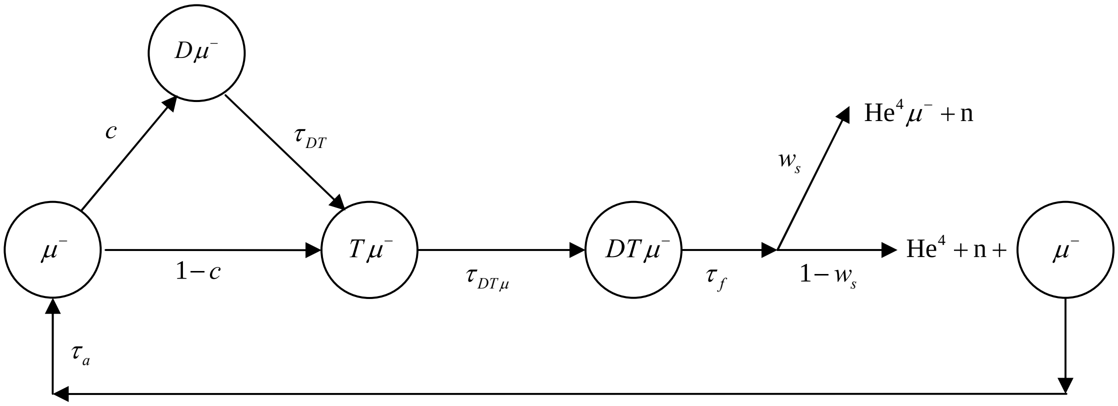

Figure 1. Reaction scheme of muon catalysis.

ion $\left(DT\mu^-\right)^+$. It takes a short time τ_f for an exothermic nuclear fusion reaction, namely D + T → He^4 + n, to occur. With probability w_s the muon is captured by He^4 and stays there until it decays as illustrated by Eq. (5). Alternatively, with probability $\left(1-w_s\right)$ the muon slows down during the time τ_a and once again catalyzes the fusion. The muon spends most of the cycle within meso atoms. The fusion time τ_f, which is very small[8] due to the existence of a nuclear resonance, i.e. $\tau_f \sim 10^{-12}\,\mathrm{sec}$, and the time of slowing down and capture, namely $\tau_a \sim 10^{-10}\,\mathrm{sec}$, are negligibly small compared to the muon life time, τ_0, which we recall from Eq. (5) to be about 8 microseconds. The density dependent quantities, τ_a, τ_{DT} and $\tau_{DT\mu}$ noted above, are for a gas of liquid hydrogen density, i.e. 4.25×10^{22} cm^{-3}. The probability w_c that the muon quits the cycle is the sum of three quantities, each being the product of the probability for the corresponding meso atom formation and the probability of muon decay inside that atom. Noting that τ_{DT}, $\tau_{DT\mu} << \tau_0$, the quantity w_c may be written as

$$w_c = c\frac{\tau_{DT}}{\tau_0} + \frac{\tau_{DT\mu}}{\tau_0} + w_s \tag{6}$$

and the number of cycles which a muon has time to catalyze is $x_c = 1/w_c$. According to theoretical estimates[8], $w_s \le 10^{-2}$ and $\tau_{DT} \sim 5\times10^{-9}\,\mathrm{sec}$ for liquid hydrogen density. Moreover, it has been shown that at these densities $\tau_{DT\mu} \le 10^{-8}\,\mathrm{sec}$, which is also small compared to the muon life time τ_0. Experiments have shown that $w_c \approx 10^{-2}$, in other words, one muon can catalyze $x_c \approx 10^2$ fusion reactions releasing about 2 GeV of energy.

II. Concept Description

We utilize this brief underlying physics analysis to propose a fusion propulsion system which derives its energy from muon-catalyzed fusion in a DT plasma which can also serve as the propellant. The system will consist of a magnetic mirror device of the gasdynamic (GDM) type connected to an antiproton-housing chamber, "traps", as shown in Fig. 2. The choice of GDM as the magnetic confinement device is especially important since it lends itself to stable containment of high density plasma as is the case here. An antiproton trap that will be suitable for the proposed system will be tailored along the lines of an existing device called the High Performance Antimatter Trap (HiPAT) which can hold up to 10^{12} antiprotons at 20 keV energy and which has already been developed and currently being tested.[*] In addition to the energy released by the muon-catalyzed fusion reactions, the propellant will be heated by the fission fragments and the pions, among others, resulting from the "at rest" annihilation of antiprotons in U^{238} targets. Because of the presence of the magnetic field, these particles will be confined and can

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[*] Jackson, G., Hbar Technologies, Chicago, IL, private communications, 2005.

instantly interact and heat a dense, low temperature DT plasma. Such a plasma will be inserted into the GDM just prior to ejecting the antiprotons from the trap to strike the U^{238} target and initiate the "at rest" annihilation reaction.

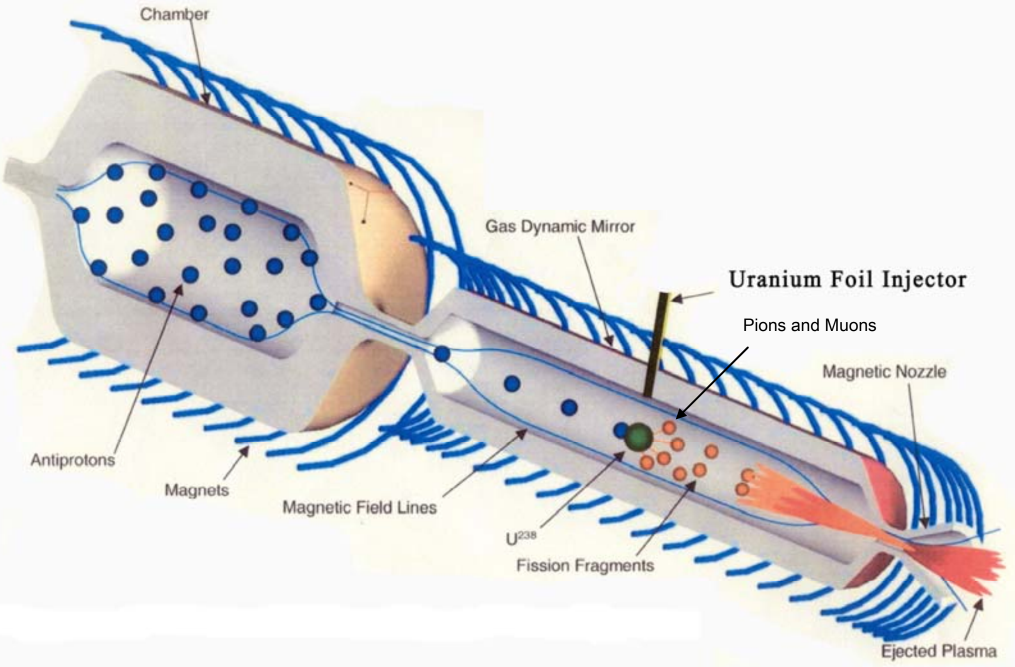

Figure 2. Muon-boosted fusion propulsion system.

As noted earlier, the generated pions decay into muons in about 72 nanoseconds giving rise to an equal number of muons, half of which can carry out the catalysis illustrated in Fig. 1 for the duration of their lifetime. Because of their comparatively long decay time, these particles also contribute significantly to the heating of the DT plasma in the mirror machine. Such heating, along with that contributed by the fission fragments as well as by the alpha particles produced by the catalyzed fusion, can heat the plasma to high enough temperatures to make it suitable for propulsion application. At the liquid hydrogen densities, noted earlier, and the appropriate temperature, the system will be modest in size and still produce sizable amounts of thrust. This is, in part, due to the fact that the Gasdynamic Mirror is a confinement device that has been shown to stably support large "β" plasmas, where β is the ratio of plasma pressure to magnetic field pressure.

The reason that high density plasma is particularly suited for confinement in the Gasdynamic Mirror is the underlying confinement principle which demands that the ion-ion collision mean free path be much shorter than the plasma length. Under these conditions the plasma behaves much like a fluid (gas in this case), and its escape from the system would be analogous to the flow of a gas into vacuum from a vessel with a hole. The condition for plasma confinement in GDM is given by[9]

$$\frac{\lambda}{R} << L \tag{7}$$

where λ is the collision mean free path, L the length of the plasma, and R the plasma mirror ratio defined by

$$R = \frac{R_0}{\sqrt{1-\beta}} \tag{8}$$

In the above expression, R_0 denotes the vacuum mirror ratio, and as mentioned above β denotes the ratio of the plasma pressure to the (vacuum) magnetic field pressure. An expression of λ appropriate for the system under consideration can be written as

$$\lambda\left(\text{cm}\right) = 1.25\times10^{18}\,\frac{T^2\left(\text{keV}\right)}{n\left(\text{cm}^{-3}\right)} \tag{9}$$

so that for a plasma of one keV temperature, for example, and 10^{22} cm^{-3} density, $\lambda \sim 10^{-4}$ cm, a very small quantity indeed consistent with the property of a continuum. Experiments[10] have shown that very large β (~0.90) plasma can be effectively confined in the GDM where no large scale instabilities of any sort that could lead to rapid plasma breakups had been detected. Moreover, an explicit expression for plasma confinement in GDM can be shown to have the form[11]

$$\tau_c = \frac{RL}{v_{th}} \tag{10}$$

where v_{th} is the ion mean velocity, and R and L as defined earlier. It is interesting to note from Eq. (10) the dependence of the confinement time in GDM on the plasma mirror ratio R rather than on its logarithm as is the case with the "collisionless" mirror. Also in contrast to the collisionless mirror, τ_c varies inversely with the square root of the ion energy rather than directly with the energy to the 3/2 power, and directly on L which is totally absent in the collisionless mirror case. This dependence on the length is particularly significant since it provides an additional parameter with which to adjust confinement as needed.

III. Conclusion

In summary, we envisage a fusion propulsion device such as that displayed in Fig. 2, where fusion reactions are initiated by the muons generated as a result of the fissioning of U^{238} nuclei by the "at rest" annihilation of antiprotons striking the uranium target. Additional heating of the DT plasma, which also serves as the propellant, is provided by the energetic and ionizing fission fragments produced by that process in addition to that contributed by the pions (before their decay into muons) as well as other particles. It is expected that sufficiently high temperatures can be reached by this approach which, when coupled to the high density requirement of the catalysis process, will lead to a very promising propulsion system as characterized by high thrust and high specific impulse. When applied to a one-way mission to Mars, for example, preliminary estimates show that it can be accomplished in about one month and require a few micrograms of antiprotons.

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