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A New Concept for Muon Catalyzed Fusion Reactor

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Abstract

A new concept for a muon catalyzed pure fusion reactor is considered. To our best knowledge this constitutes a first plausible configuration to make energy gain without resorting to fissile matter breeding by fusion neutrons, although a number of crucial physical and engineering questions as well as details have yet to be resolved. A bundle of DT ice ribbons (with a filling factor f) is immersed in the magnetic field. The overall magnetic field in the mirror configuration confines pions created by the injected high energy deuterium (or tritium) beam. The DT material is long enough to be inertially confined along the axis of mirror. The muon catalyzed mesomolecule formation and nuclear fusion take place in the DT target, leaving α^{++} and occasionally $(\alpha\mu)^{+}$ (muon sticking). The stuck muons are stripped fast enough in the target, while they are accelerated by ion cyclotron resonance heating when they circulate in the vacuum (or dilute plasma). The ribbon is (eventually) surrounded and pressure-confined by this coronal plasma, whereas the corona is magnetically confined. The overall bundle of ribbons (a pellet) is inertially confined. This configuration may also be of use for stripping stuck muons via the plasma mechanism of Menshikov and Ponomarev.

I. Introduction

In order to achieve a thermodynamically meaningful energy gain by muon catalyzed DT fusion alone without resorting to breeding fissile matter by fusion neutrons, it is believed that the fusion catalysis cycling rate in a muon lifetime, X_μ, needs to substantially exceed 1000, while the so-called break even (after counting the thermodynamical efficiency of energy conversion) needs X_μ between 500 and 1000 under our current understanding of the processes of muon catalyzed fusion. Neglecting faster intermediate processes, nowadays we can identify two crucial bottlenecks for muon catalyzed fusion energy production. The one is the $dt\mu$ mesomolecular formation process (rate $\lambda_{dt\mu}$) and the other is the muon sticking with fusion α particles (probability ω_{s0}):

$$X_\mu^{-1} = \omega_s + (\lambda_{dt\mu}\tau_\mu)^{-1} , \tag{1}$$

where

$$\omega_s = \omega_{s0}(1-R) , \tag{2}$$

and τ_μ is the lifetime of a muon and R is the stripping rate of muon from the $(\alpha\mu)^+$ atom.

In recent years best estimated experimental and theoretical values for ω_{s0}, R, and $\lambda_{dt\mu}$ have steadily firmed and are presently converging toward each other, as well evidenced in the presentations of the present Workshop:[1,2] $\omega_{s0} \simeq 0.008$, $R \sim 40\%$, and $\lambda_{dt\mu} \sim 10^9\,\mathrm{sec}^{-1}$. The formation rate $\lambda_{dt\mu}$, of course, is a function of density ϕ and can be a function of temperature T as well. The exponent to ϕ may be larger than unity, although not enough is known. The exponent to T may also be positive and it may change in the regime higher than the room temperature. Again it is not for certain. In much higher temperature regime different molecular formation physics come into play and the mesomolecule can be destroyed by collisions. Some of the processes involve a plasma and three-body collisions.[3,4] These new channels of molecule-plasma reactions are potentially of immense importance, as their rates could be respectably large,[4] in spite of mesomolecule destruction. They tend to peak near temperatures of 10^1 eV. At present, however, no firm experimental investigations of these as we know of exist. Although we witness new infusion of physics in the mesomolecule formation processes and some degree of uncertainty in their rates, it is fair to say that the debate on understanding of the severest bottleneck of all, the sticking rate, has now been experimentally and theoretically settled at least to a degree accurate enough to decide the rate of energy production: $\omega_s \sim 0.0045$. This entails that even if $\lambda_{dt\mu} \to \infty$, the catalysis cycle rate X_μ is merely ~ 220. A very nice scientific progress in advancing the understanding of sticking physics. Nevertheless, a disappointing conclusion in itself.

The next question is: if the nature gives us a value of $X_\mu \sim 220$ (or lower), is it possible to enhance it by an ingenious method or two? Roughly speaking, the determination of ω_{s0} involves nuclear physics along with $dt\mu$ molecular dynamics; that of R involves atomic and molecular physics, while that of $\lambda_{dt\mu}$ includes atomic and molecular physics. Thus it seems prudent to us to try to "manipulate" or improve the processes that pertain to lower energy physics, i.e., atomic and molecular physics, as it is easier (or "cheaper") to influence lower energy physics. This is one of our guidelines. In the following we consider the enhancement of stripping by one way or another that does not involve nuclear physics.

Before we proceed to discuss our concept, we feel obligated to emphasize the famous but oft forgotten thermodynamical theorem, the second law of thermodynamics. Sometimes the muon catalyzed fusion is said to be *cold* fusion. This is appropriate only for the fundamental processes. As far as energy production is concerned, if it is too cold, no energy gain is possible to achieve (under 'normal' circumstances). Imagine that we want to let fusion happen in DT ice bars (below 25K). Per a dt fusion reaction, a neutron of 14.1 MeV and an alpha particle of 3.5 MeV are created. The neutron leaves the ice and presumably hits a surrounding blanket (or worse, a metal), while the alpha particle is likely to stay in the DT ice and heats it. If we are to insist on keeping the low temperature of the specimen, every time a fusion alpha particle heats the target, we have to cool (or extract the energy of that amount from) the material. That is, we have to remove 3.5 MeV energy per fusion. With the cooling efficiency η_c (because of the second law of thermodynamics, it is not unity and in fact a miniscule number typically of the order of) ~ 0.1, the necessary energy to keep the material at a desired cool temperature is $3.5\,\mathrm{MeV}/\eta_c$ ($\sim 35\,\mathrm{MeV}$) per fusion. On the other hand the total fusion energy production is of course only 17.6 MeV per fusion. No energy gain is possible. We shall come back to this difficulty when we discuss our concept.

II. Enhancement of Stripping

The effective sticking probability ω_s can be reduced by increasing the stripping coefficient R [see Eq. (2)]. The stripping (or reactivation) coefficient R may be written as[4,5,6]

$$R = 1 - \exp\left[-n \int_{E_i}^{E_b} \frac{\sigma_{\mathrm{st}}(E)dE}{F(E)}\right] , \tag{3}$$

where σ_{st} is the stripping cross-section, F is the stopping power of $(\alpha\mu)^+$ in matter, and E_b and E_i are the birth energy of $(\alpha\mu)^+(\sim 3.5\,\mathrm{MeV})$ and the $(\alpha\mu)^+$ ionization potential ($\sim 10\,\mathrm{keV}$). The cross-section peaks around $\sim 10\,\mathrm{keV}$ and quickly decreases below this energy. In order to make the reactivation coefficient large (i.e., close to unity), Bracci and Fiorentini[7] argued $(\alpha\mu)^+$ should be kept as long as possible in the higher velocity range where the stripping probability is higher. They suggested to apply accelerating electric fields in the matter. Unfortunately, the effective slowdown field in the solid matter is of the order of 45 MeV/cm, with which, either by dc or ac fields, breakdown of the target arises.

Kulsrud proposed[8] a clever separation of the target and the vacuum section in which acceleration of $(\alpha\mu)^+$ atoms takes place while their stripping happens in the solid (or liquid) target. The acceleration is achieved by the ion cyclotron resonance heating with the frequency $\omega = \Omega_{\alpha\mu} = eB/4m_p c$, where m_p is the proton mass. In his calculation the necessary strength of rf electric field $E_{\rm st}$ for stripping is

$$eE_{\rm st} \cong 5 \times 10^4 f \text{ kV/cm} , \tag{4}$$

where f is the filling factor of the DT target. On the other hand, the breakdown field for ac field E_{bd} (which is much higher than the dc case) is approximately given[9,10] by

$$eE_{bd} \simeq m\omega c , \tag{5}$$

where m is the electron mass and ω the rf frequency. At the frequency range of $\Omega_{\alpha\mu} \sim 10^{10}$ Hz (with 1M Gauss magnetic field) the field in Eq. (4) is tolerable against breakdown. Unfortunately, his idea does not work as he put it, since the alpha heating of the target cannot be tolerated, as we discussed the cooling energy in the Introduction.

Menshikov[4] proposed an alternative idea for stripping. Instead of keeping the energy of $(\alpha\mu)^+$ high by acceleration (Refs. 7 and 8), he replaces the condensed matter by a (very high density) plasma. He points out that the plasma process significantly enhances the stripping if the temperature of the plasma is $\gtrsim 10$ eV. However, he fails to provide any plausible mechanism to confine such a high pressure plasma, except for mentioning vaguely about a shock wave.

In this paper we present a plausible confinement scheme that allows significant stripping by Kulsrud's mechanism (or perhaps Menshikov's) and simultaneously maintains favorable catalysis-reaction conditions of high densities and temperatures of the target. In principle, such a system can produce energy in a thermodynamically meaningful fashion.

III. Reactor Concept

In what follows we depict only the essence of the idea, as this paper does not have enough room to discuss all the relevant issues in detail. A detailed discussion will become available later.[11] The overall configuration is given in Fig. 1.

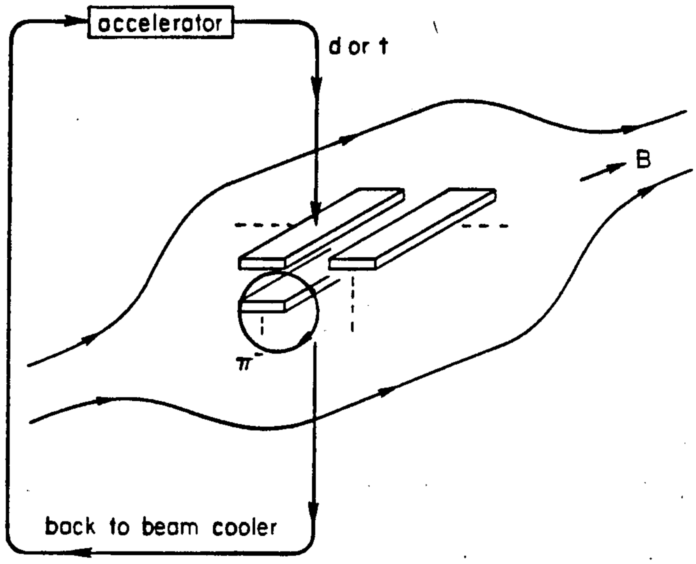

Figure 1: The overall reactor concept. The magnetic mirror axis coincides with the DT ice specimen axis. The injection direction of high energy beams of d or t is perpendicular to this. The blanket surrounds the mirror.

A simple mirror of mirror ratio R_m with magnetic field $\mathbf{B}$ generated by superconductors is surrounded by neutron blankets such as Li etc. Although the strength of the magnetic field is not uniquely fixed, we may use a typical number of 1MG. A pellet (or pellets) of DT ice is repetitively injected either mechanically or gravitationally into the mirror vessel. The pellet consists of a series of ribbons of DT ice. The minimum overall size is $\sim$(2cm)^3, which is determined by the two conditions, the inertial confinement condition of the overall pellet and the magnetic confinement condition of π^-. These DT ice ribbons fill the pellet with the filling factor f in order to accommodate sufficient acceleration time, while keeping enough matter to strip $(\alpha\mu)^+$ according to Kulsrud's mechanism of stripping. The choice of the filling factor f will be different for Menshikov's idea.[11] These DT ice specimens are penetrated by a high energy beam of d or t particles ($\sim$ 1 GeV/nucleon) injected perpendicular to the mirror axis, which coincides with the (longitudinal) axis of the specimens. Beam particles collide with the target nuclei, creating π^-'s. Pions are created *in situ* and confined by the mirror magnetic field, as in the earlier hybrid reactor concept.[12] The portion of the beam that did not suffer strong interaction will be collected, cooled, accelerated, and reused for the next pass. At this energy of the d or t beam the cooling may be appropriately provided by Budker's electron cooling method[13] or Van der Meer's stochastic cooling method.[14] The energy cost of this cooling will be studied in the future. The beam energy has to be boosted as well.

The ribbons have the following characteristics. The thickness ℓ_1 of a ribbon should be smaller than the range of $(\alpha\mu)^+$ at the 3.5 MeV energy at birth. Typically we choose 100 μm. The width ℓ_2 is typically several times ℓ_1. The length ℓ_3 is determined by the larger of the inertial confinement length and a few π^- Larmor radius:

$$\ell_3 = \max(c_s \tau_\mu \; , \; 4\rho_\pi) \; , \tag{6}$$

where c_s is the sound speed of the DT specimen and $\rho_\pi = \beta c/\Omega_\pi$. For 1 MG field and 1 eV DT specimen, these two are in the same ball park of $\sim 10^0$ cm. These ribbons are stacked up as shown in Fig. 2. The distance d_2 between two ribbons in the width direction is

$$d_2 = \min(2\rho_{\alpha\mu} \; , \; \ell_2/\sqrt{f}) \; , \tag{7}$$

and the distance d_1 between two ribbons in the thickness direction is

$$d_1 = \max\left(\ell_1/\sqrt{f} \; , \; \frac{\ell_1 \ell_2}{2f\rho_{\alpha\mu}}\right) \; , \tag{8}$$

where $\rho_{\alpha\mu}$ is the Larmor radius of $(\alpha\mu)^+$. Typical numbers for these are 0.4 cm and 0.2 cm, respectively. Radio frequency electromagnetic waves with frequency $\omega = \Omega_{\alpha\mu}$ are applied with the electric field rotating in the plane of Fig. 2.

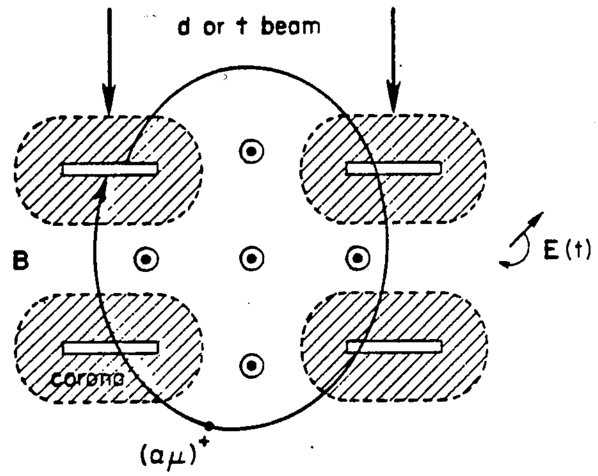

Figure 2: The array of DT ice ribbons and coronal plasma surrounded by the magnetic field.

When the beam is injected into these ribbons and fusion reactions begin, fusion alpha particles are created and all their energy is deposited in the heating of DT ice. In order to avoid the dilemma of 'cold fusion — no energy production' mentioned in the Introduction, the DT ribbons are heated up to temperature T_h which is much higher than the room temperature T_r so that we can now *extract* energy from the DT ribbon instead of investing energy to cool it. This condition is written as

$$\eta_h \Delta T_h - \Delta T_c / \eta_c > 0 \ , \tag{9}$$

where η_h and η_c are the thermodynamical efficiencies of the heat energy extraction from the hot material (T_h) into electricity and the cooling, and $\Delta T_h = T_h - T_r$ and $\Delta T_c = T_r - T_{\rm ice}$. From this T_h has to be larger than $1 - 2\,\mathrm{eV}$ for $\eta_h \sim 0.3$ and $\eta_c \sim 0.1$. This will resolve the difficulty of Kulsrud's idea. Of course, this brings in a new difficulty of confining hot DT ribbons at nearly the solid density to cope with an enormous pressure.

In order to confine these DT ribbons, we introduce the concept of coronal confinement.

We surround each ribbon with a coat of a coronal plasma with density n_c and temperature T_c such that

$$n_h T_h = n_c T_c \ , \tag{10}$$

where n_h and T_h are the heated DT ribbon density ($\phi \sim 1$) and temperature ($\lesssim 1\,\mathrm{eV}$). The thickness ℓ_c of the coronal plasma is

$$\ell_c \simeq \frac{1}{4} d_1 \ . \tag{11}$$

We choose the density of the corona such that the majority of $(\alpha\mu)^+$ of stripping does not take place there:

$$n_c \ll \frac{\ell_1}{\ell_c} n_h \qquad \text{and} \qquad T_c \gg \frac{\ell_c}{\ell_1} T_h \ . \tag{12}$$

Equation (12) can be written as

$$n_c \ll \frac{4\ell_1}{d_1} n_h = 4\sqrt{f}\ n_h \qquad \text{and} \qquad T_c \gg \frac{1}{4\sqrt{f}} T_h \ , \tag{13}$$

where the equality in Eq. (13) applies when the first term in the parenthesis in Eq. (8) applies. T_c typically is $10\,\mathrm{eV}$. When the DT ribbon expands after alpha heating, the coronal pressure balances it, while the coronal pressure is now borne by the magnetic pressure outside of it. Thus, the corona is magnetically confined:

$$n_c T_c + \frac{B_c^2}{8\pi} = \frac{B^2}{8\pi} \ , \tag{14}$$

where B_c is the magnetic field penetrated into the corona and B is that of outside ($\sim$ vacuum). Details of the creation method of such a corona will be discussed elsewhere. Some possibilities include the alpha heating of the ribbon itself with or without a sponge-like surface, injection of very hot and very tenuous plasma to evaporate the surface, surface current application, laser surface ablation, etc.

The magnetic field tends to penetrate into the corona (and the ribbon) by the resistive process. The velocity of such penetration v_p is given by

$$v_p = \frac{\eta c \nabla P_c}{B^2} \sim \frac{\eta_0 c (n_h T_h)/\ell_c}{B^2 (T_c/T_0)^{3/2}} , \tag{15}$$

where η is the collisional resistivity of the corona and an explicit dependence of the coronal temperature is written in. This velocity should be sufficiently small such that

$$\ell_c / v_p > \tau_\mu . \tag{16}$$

This equation imposes a constraint on B, ℓ_c, T_h, and T_c. Besides the classical resistive penetration, there may arise anomalous penetration. A most prominent example is due to the Rayleigh-Taylor instability developing at the corona-vacuum interface, as the expanding corona decelerates due to the magnetic pressure. A simple estimate of the growth rate of the R-T instability is

$$\gamma \simeq \alpha \sqrt{g/\ell_c} \sim \alpha c_s / \ell_c , \tag{17}$$

where α is a geometrical factor ordinarily less than unity. There may be a possibility of developing an electric field and the coronal plasma penetrate through the magnetic field with $cE \times B/B^2$ drift velocity. In this case it may become necessary to short out the electric field.[15] Detailed considerations of these will be referred to later publications.[11] Finally, the collection of all these ribbons is confined inertially

$$\ell_3 / c_s \simeq a / c_s > \tau_\mu , \tag{18}$$

where a is the size of the pellet.

IV. Conclusion

We have presented a first plausible concept for fusion reactor via muon catalysis. It tries to reduce the effective sticking probability much less than 10^{-3} by the ion cyclotron resonance heating (or perhaps by the plasma stripping effects). The necessary structure of the DT fuel was elaborated. This particular structure allows the above operation, simultaneously keeping the necessary criteria for the mesomolecule formation processes. A number of parameters such as the strength of magnetic field, the filling factor etc., have yet to be optimized. It is entirely possible, however, that a comfortable (for physics) choice of parameters may lead to the requirement of a fairly large magnetic field of the order of 1 MG. Many anomalous plasma related processes may come into play. The rf power may be dissipated by extraneous resonances and other unwanted heating and thus the Q-value of rf source may not be as high as we wish. All these physical as well as technical problems can be formidable and certainly provide an immense challenge. The work is cut out for us. Nonetheless we are happy to point out that a major line of our concept has still withstood various conceivable difficulties in an essential way up till now.

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