THE MUON-CATALYZED NUCLEAR ENERGY SYSTEM

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ABSTRACT

Muon-catalyzed fusion has recently emerged as an interesting fusion energy system prospect. Experimental results and parametric analyses have provided the essential justification for its continuing development. We consider here this distinctive nuclear energy option with an emphasis on the underlying reaction and energy systematics and their consequent implications for engineering analysis.

INTRODUCTION

The current main-line approaches to the realization of nuclear energy based on fusion reactions rely upon magnetic and inertial force effects. Each of these approaches is characterized by a dominant physical constriction; for the former it is the efficiency of containment of ions against their mutual electrostatic repulsion while for the latter it is the efficiency of coupling beam energy with the kinetic energy of the ions in the pellet. These effects are in stark contrast to fission reactions which proceed at nominal temperatures without any external energy requirements.

It is therefore a tantalizing notion to consider a fusion reactor cast into the conceptual framework of a fission device. With the considerable experience of fission systems, one might view such a nuclear energy alternative as an adaptation of an existing reactor technology to a fusile fuel cycle. The fundamental requirements then rest on the reduction of Coulomb repulsion among the fusion hydrogen isotopes. It is now recognized that the negatively charged subnuclear mu-meson -- commonly called the "muon" and represented by the symbol μ -- serves this purpose very well.

Muon-catalyzed fusion is based on the concept of nuclear catalysis, that does, in a manner, resemble chemical catalysis with the muon serving the function of enabling a selected nuclear reaction to occur. For the fusion reaction between a deuteron d and a triton t, we may therefore write

$$\begin{tikzcd}[column sep=small] d + t + & \mu \arrow[r] & (\;) \arrow[r] & \mu \arrow[ll, bend left] & + n + a \end{tikzcd} \qquad (1)$$

with a reaction Q-value of 17.6 MeV. As in chemical catalysis, the nuclear catalyst μ is here recovered from among the reaction products and may, repeatedly, catalyze further $d+t$ reactions. We reemphasize the important point that the above catalytical fusion reaction is an experimental fact observable, for example, in a liquid deuterium and tritium mixture at room temperature.

HISTORICAL ORIGIN AND PHYSICAL BASIS

The suggestion that a muon might be an important component in an alternative approach to fusion was first made by Frank (1) and immediately generated sustained interest primarily in the USSR (2-5). Even with its experimental demonstration established (6) it was nevertheless viewed with some caution for reason of inappropriate cross section and muon life-time (7).

In 1977, the perception of the practical uses of muon catalysis changed when a pronounced resonance in a reaction channel was predicted (8) and experimentally confirmed (9). Increasing interest has thereupon been shown in this subject (10-12).

The fundamental features which will determine the "form and shape" of a muon-catalyzed fusion system are determined by the properties of the muon and its interaction phenomena; the deuterium and tritium requirements as well as the neutron and alpha products and reaction Q-values are unchanged from conventional magnetic and inertial $d+t$ fusion.

Muons appear as decay products from a number of high energy reactions in accelerator targets. A suitable muon collection channel directs the muons into the $\mu+d+t$ reaction chamber. Three properties of a muon are important:

$$\text{Lifetime: } \tau_\mu = 2.2\times10^{-6}\,\text{s} \qquad (2.\text{a})$$

$$\text{Charge} \;:\; q_\mu = q_e \qquad (2.\text{b})$$

$$\text{Mass} \;:\; m_\mu = 207\, m_e \qquad (2.\text{c})$$

Though a mean-life of 2.2×10^{-6} s is commonly viewed as very short, it is nevertheless very long compared to nuclear reaction rates.

The property that a muon possesses the same charge as an electron, $q_\mu = q_e$, and a mass 207 times that of an electron, means that the muon can enter into a very tight Bohr orbit with a radius 207 smaller, Fig. 1. Hence a muonic hydrogen atom appears to possess some of the properties of an oversize neutron and may therefore approach another hydrogen sufficiently closely -- without the repulsive Coulomb force becoming dominant -- until the short range nuclear forces of attraction render fusion very likely.

REACTION NETWORK

When a high energy muon enters a deuterium-tritium mixture, it quickly loses energy and is captured in a hydrogen orbit. Two muon-hydrogen "capture-type" reactions are possible, one with deuterium and one with tritium.

$$\mu + d \rightarrow \mu d \qquad (3.\text{a})$$

$$\mu + t \rightarrow \mu t \qquad (4.\text{n})$$

These muonic atoms, μd and μt, may now combine with either a deuteron or triton to form muonic molecules as follows:

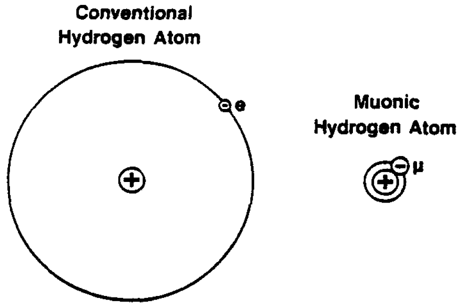

FIGURE 1: GRAPHICAL COMPARISON BETWEEN A CONVENTIONAL HYDROGEN ATOM AND A MUONIC ACTION; THE RADII ARE IN A RATIO OF 1/207 AND HENCE THIS FIGURE IS NOT TO SCALE.

$$\begin{Bmatrix}\mu d\\ \mu t\end{Bmatrix}+\begin{Bmatrix}d\\ t\end{Bmatrix}\rightarrow\begin{Bmatrix}\mu dt\\ \mu dd\\ \mu tt\end{Bmatrix} \qquad (4)$$

The formation of μdt -- and hence its decay fusion products -- is the most likely process though all three muonic molecules may form and subsequently disintegrate (13).

Three additional proccesses need to be considered. There exists the exchange reaction

$$\mu d + t \rightarrow \mu t + d \qquad (5)$$

The ever-present decay of a muon -- whether bound or not

$$\mu(\ ) \rightarrow (\ ) + e + \nu_e + \nu_\mu \qquad (6)$$

and finally the very important alpha-sticking in which a muon becomes firmly attached to the ^{4}He nucleus to terminate the catalytic chain:

$$dt \rightarrow \begin{cases} \overset{\omega}{\nearrow}\ \mu\alpha + n \\ \searrow\ \mu + \alpha + n \end{cases} \qquad (7)$$

Here, ω is the channel probability for muon-sticking to the alpha particle.

Detailed calculations involving all conceivable reaction channels (13) have shown that a reduced linkage (11) provides an adequate description of the energetic of the muon-catalyzed fusion process. We depict this reaction network in Fig. 2 where we also identify the rate parameter associated with particular reactions; note the notation of using straight arrows for "compound-nucleus formation" processes and wavy arrows for "nuclear decay".

Finally, we point to the feature that both Fig. 2, as well as Eq. (1), possess the essential features of a fission reaction cycle.

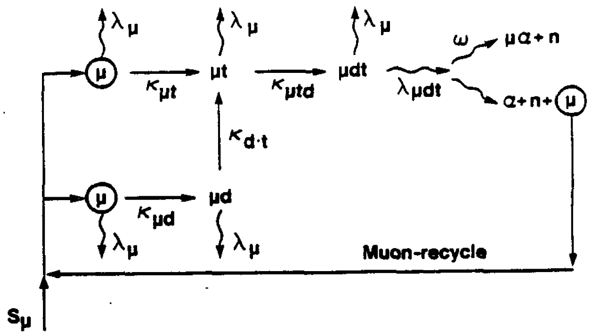

FIGURE 2: MUON-CATALYZED d+t REACTION NETWORK SHOWING ALSO MUON INJECTION RATE S_μ FROM AN EXTERNAL SOURCE.

$$n + {}^{235}U \rightarrow ({}^{236}U)^* \rightsquigarrow \begin{cases} \nearrow\ {}^{236}U + \gamma \\ \searrow\ \nu n + P_1 + P_2 \end{cases} \qquad (8)$$

An important distinction for this fission cycle is that the chain carrier is multiplied in the process and can be considered stable (on the time scale of a fission cycle); both of these properties are absent in the muon-catalyzed fusion cycle. The important property of reaction cycle of muon-catalyzed fusion reaction sustainment at nominal temperature and in condensed matter is, however, retained.

REACTION ENERGETICS

The overall energy balance of a muon-catalyzed fusion system is related in a fundamental sense to the energetics of the reaction cycle, Fig. 2. Energy supplied to sustain the reaction cycle and the energy liverated in the reaction process are the two determining parameters. We consider therefore the energy multiplication defined by the ratio

$$M_E = \frac{E_{out}}{E_{in}} \qquad (9)$$

Expressing E_{out} and E_{in} normalized to one muon, then E_{in} is the average energy cost of producing a muon in the accelerator, E_μ, and E_{out} is the average number of d+t fusion reactions one muon might catalyze,X_μ, multiplied by the Q-value of the d+t reaction, Q_{dt}; we write therefore

$$M_E = \frac{X_\mu Q_{dt}}{E_\mu} \qquad (10)$$

while Q_{dt} = 17.6 MeV and E_μ is typically estimated to be ∿ 2500 MeV; this relation demands therefore that one muon must catalyze on average more than 2500/17.6 = 142 fusion reactions during its lifetime of 2.2×10^{-6} s. This will evidently depend upon the various cross sections as represented by the reaction rate parameters $K_{()}$ and $\lambda_{()}$ of Fig. 2.

An analytical expression for X_μ can be established by the following argument. Consider a muon injection rate $S_\mu(t)$ to the fusion chamber and that this injection results in a fusion "decay" rate of $(dN_{\mu dt}/dt)$. The fraction $(1-\omega)$ of these will release the muon for another cycle, Fig. 2. Allowing for time variation in the muon injection rate and fusion-decay rate therefore defines

$$X_\mu = \frac{(1-\omega) \int (-dN_{\mu dt}/dt)dt}{\int S_\mu(t)dt} \tag{11}$$

where the integration is one-to-one for muon injection and its ensuing sequence of muon catalyzed fusion chains.

A useful simplification is here possible since

$$-dN_{\mu dt}/dt = \lambda_{\mu dt} N_{\mu dt}(t) \tag{12}$$

where $N_{\mu dt}$ is the muonic molecule density μdt as a function of time and $\lambda_{\mu dt}$ is its decay constant. We write therefore, the general expression for the energy multiplication, Eq. (10)

$$M_E = \frac{(1-\omega) Q_{dt} \lambda_{\mu dt} \int N_{\mu dt}(t)dt}{E_\mu \int S_\mu(t)dt} \tag{13}$$

and now require a reaction kinetics analysis to determine $N_{\mu dt}(t)$ and also to specify $S_\mu(t)$.

The point kinetics description for the reaction network of Fig. 2 requires the identification of rate equations for the densities of each of the component specie N_μ, $N_{\mu d}$, $N_{\mu t}$ and $N_{\mu dt}$. These rate equations can be shown to be given by the following set:

$$\frac{dN_\mu}{dt} = S_\mu + (1-\omega)\lambda_{\mu dt} N_{\mu dt} - K_{\mu t} N_\mu N_t - K_{\mu d} N_d N_\mu - \lambda_\mu N_\mu \tag{14a}$$

$$\frac{dN_{\mu d}}{dt} = K_{\mu d} N_\mu N_d - \lambda_\mu N_{\mu d} - K_{d \cdot t} N_{\mu d} N_t \tag{14b}$$

$$\frac{dN_{\mu t}}{dt} = K_{\mu t} N_\mu N_t + K_{d \cdot t} N_{\mu d} N_t - \lambda_\mu N_{\mu t} - K_{\mu dt} N_{\mu t} N_d \tag{14c}$$

$$\frac{dN_{\mu dt}}{dt} = K_{\mu dt} N_{\mu t} N_d - \lambda_\mu N_{\mu dt} - \lambda_{\mu dt} N_{\mu dt} \tag{14d}$$

A particularly useful -- and convenient -- solution is possible for the case of steady-state analysis; that is, a steady-state tritium injection is taken to occur and equilibrium concentrations of N_μ have been attained. For this case, Eqs. (14) can be solved explicitly for the ratio $N_{\mu dt}/S_\mu$ to give

$$\frac{N_{\mu dt}}{S_\mu} = \frac{1}{\lambda_{\mu dt}(\omega + A - 1)} \tag{15}$$

Here A is an involved function of the reaction rate parameter K_μ and λ_μ, (Ref. (14).

For this case then, the energy multiplication M_E of Eq. (13) becomes

$$M_E = \frac{(1-\omega)\lambda_{\mu dt} Q_{dt}}{S} \left(\frac{N_{\mu dt}}{S_\mu}\right)$$

$$= \frac{(1-\omega)}{(\omega + A - 1)} \left(\frac{Q_{dt}}{E_\mu}\right) \tag{16}$$

Our analysis of the latest experimental data set at 500 K in a liquid hydrogen density at 10^8 Pa (Refs. 15-16) suggests the following energy multiplication

$$M_E = \frac{(1-7.6\times10^{-3}}{(7.6\times10^{-3} + 1.8\times10^{-3})} \left(\frac{17.6}{2500}\right)$$

$$= 0.74 \tag{17}$$

Thus, based on only some 5 years of experimental investigations, an energy break-even almost exists. We add, however, several points. All experimental data suggest an upward trend in M_E and X_μ with increasing temperature and our extrapolation suggests a break-even at about 900 K. Further, E_μ of ∿ 2500 MeV is highly uncertain deserving of considerable further examination. Finally, the energy multiplication above does not incorporate any energy credit from the use of a fraction of the fusion neutron for fissile fuel breeding purposes; that is, this muon-catalyzed fusion reactor may be viewed as a hybrid or symbiont (11,17).

SYSTEM DESIGN

Design of a muon-catalyzed fusion reactor system is dominated by the need for an on-line accelerator to produce pi-mesons which decay into the desired muons. In this respect the power flow pattern resembles that of an inertial confinement fusion system or of a spallation-aided fission system, Fig. 3.

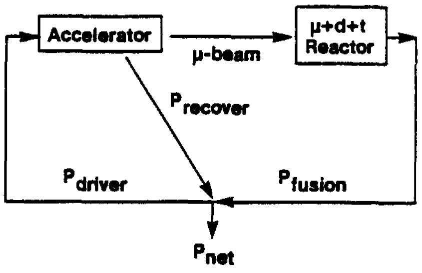

FIGURE 3: POWER FLOW FOR A MUON-CATALYZED FUSION REACTOR.

While a generally accepted design has yet to emerge (18-21), we can conceive of a broad systems outline as depicted in Fig. 4.

Muon production by pion decay ($\tau_\pi = 10^{-8}$ s) appears the only practical choice. Hence light ions (p,d, or t) of energy in excess of ∿ 1 GeV will strike a low atomic mass number target with the transmitted ions either recirculated by magnetic forces or allowed to impact upon one or more successive

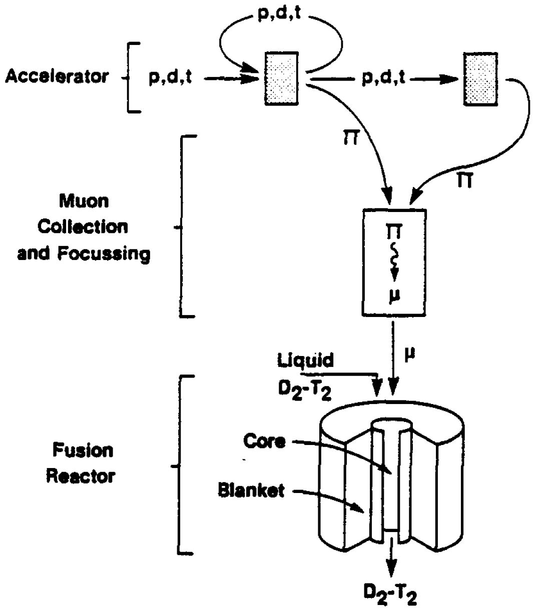

FIGURE 4: SUGGESTED DEPICTION OF MAIN COMPONENT OF A MUON CATALYZED FUSION REACTOR SYSTEM.

targets of increasing atomic mass, Fig. 4. The pi-meson will be emitted with a highly anisotropic directional distribution to be collected for decay into muons

$$\pi \rightarrow \mu + \nu_\mu \qquad (18)$$

The muons thus produced would be collected and focussed onto a cylindrical fusion core consisting of liquid deuterium and tritium under pressure of $\sim 10^8$ Pa and at a temperature of $\sim$ 900 K, Fig. 4. This cylindrical fusion core will be surrounded by a blanket which serves, variously and as required, the functions of (i) tritium breeding, (ii) fissile fuel breeding, and (iii) energy removal.

Note that the fusion reactor part, Fig. 4, possesses some resemblance to a CANDU fission reactor with a single pressure tube and breeding blanket.

Current technology suggests that both the accelerator and the fusion reactor pose few serious problems; it is however, the (i) pion-to-muon collector, (ii) focussing of muons into the fusion core, and (iii) the efficient recovery of residual energy in the accelerator target that poses the challenge.

CONCLUDING COMMENT

Recent experimental results of muon-hydrogen reactions suggest a firm basis for the potential viability of muon-catalyzed fusion as an alternative nuclear energy systems. While a number of systems components follow directly from existing technology, there exist however a number of critical technical issues deserving considerable in-depth investigation.

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