MUON CATALYZED FUSION

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Abstract The state of the art and the recent progress made in $d\mu t$ fusion is shortly reviewed. Experiments demonstrated 100 to 150 dt fusions per muon. The most reliable value for dt sticking is $\sim 0.5\%$. This sets a natural limit to the possible fusion output with μCF to 200 per muon. In energy applications, the concept of Yu. Petrovs μCF hybrid reactor is sketched. There are prospects for using μCF for intense neutron sources to be used for materials testing of future hot fusion reactors and for applications in element transmutation.

1. INTRODUCTION

The idea of Muon Catalyzed Fusion (μCF) was first suggested by C. Frank [1] in 1947 in the course of examining possible alternative explanations of peculiar cosmic ray tracks in photoemulsions exposed at high altitudes, tracks that were made in fact by positive pions stopping and then decaying into muons and neutrinos. Independently, A.D. Sakharov took up the discussion of muon catalysis already in 1948 in his legendary article about "passive mesons" [2]. He recognized the basic approach of muon catalysis: Formation of closely bound molecules, inducing nuclear fusion by quantum mechanical tunnel effect. The experimental discovery of μCF was achieved at the end of 1956 in Berkeley by L.W. Alvarez' team looking at bubble chamber pictures [3], see example in fig. 1.

Contrary to "hot fusion" which requires high temperatures - more than 100 Million degrees, equivalent to 10 keV - the μCF method works with very soft energies only, i.e. mini eV to several eV, i.e. at temperatures ranging from near zero to 10^4 Kelvin. The key point is, that *stable* bound states (mesic molecules) are formed with the muon and two nuclei,

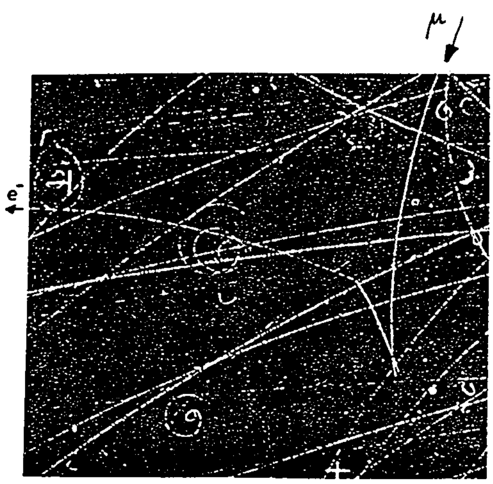

Figure 1: First bubble chamber picture of the μCF discovery by L. Alvarez et al. [3], showing a characteristic diffusion gap between stopping muon and reemitted muon after $p\mu d$ fusion.

separated by distances of about twice the muonic Bohr radius (~ 500 fro). In the ordinary D_2 molecule or in any solid state configuration the nuclei are too much apart (~ 1 Å or 10^5 fm) to cause any observable fusion rate. This is the reason why all attempts to induce powerful nuclear fusion in Palladium or Titanium saturated with deuterium which created a lot of "confusion" are hopeless [4].

There was some disappointment in the fifties and sixties - since the number of muon induced fusion events observed in bubble chambers was only a few percent per muon and seemed to make energy applications of μCF unlikely. But the interest in μCF was greatly revived by the observation at Dubna (Russia) of the temperature dependence of $d\mu d$ mesic molecule formation in 1964-66 [5] and later [6], and by its theoretical explanation [7,8] and the prediction of very large $d\mu t$ formation rates [8,9] in deuterium-tritium (dt) mixtures via the reactions

$$t\mu + D_2 \longrightarrow [(d\mu t)dee]\ (\text{rate } \lambda_{d\mu t-d}), \tag{1}$$

$$t\mu + DT \longrightarrow [(d\mu t)tee]\ (\text{rate } \lambda_{d\mu t-t}). \tag{2}$$

The recent history of the μCF development and more detailed descriptions of its present state of the art can be found e.g. in reviews [10-16]. Today's interest in μCF is predominantly focused on the most effective $d\mu t$ cycle sketched in fig. 2. Negative muons which stop in a dense dt mixture form in 10^{-12} to 10^{-13} s tiny neutral mesic atoms $d\mu$ and $t\mu$. In collisions with other nuclei the muons get transferred to the heavier isotope ($10^{-8}-10^{-10}$ s). The crucial process is the resonant formation of the mesic molecule $d\mu t$ into the loosely bound roto-vibrational state J=l, v=l [8,9] ($10^{-8}-10^{-10}$ s). This state quickly deexcites to J=O levels, from which the two nuclei fuse ($\sim 10^{-12}$ s). Usually the muon is free to start the next cycle, but occasionally (with probability $\omega_s \sim 0.5\%$) it is removed from the active cycle by *"sticking"* to the ^{4}He nucleus. The process chain in fig. 2 is much faster (cycle rate $\lambda_c >$ 108s-1) than the muon decay rate $\lambda_o = 0.455 \cdot 10^6 s^{-1}$. In principle, it allows a single muon to catal yze hundreds of dt fusions and to generate amounts of energy approaching or exceeding the cost for muon production (~ 6-8 GeV [17]). This fact has triggered great interest in energy applications of μCF.

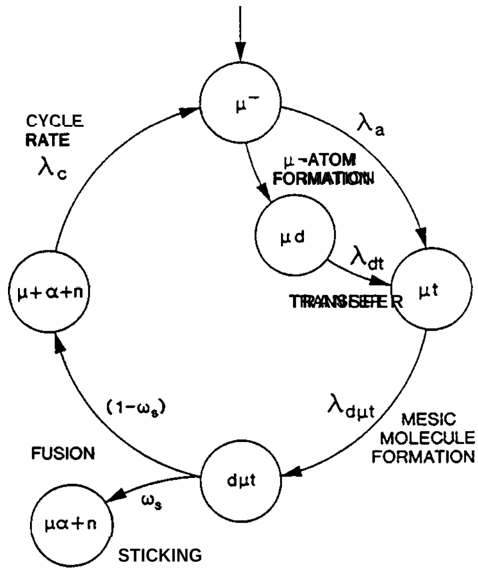

Figure 2: Simplified scheme of the deuterium tritium fusion cycle. For the symbols see text.

2. RECENT EXPERIMENTAL RESULTS IN $d\mu t$ FUSION

After the prediction [8,9] of large $d\mu t$ formation rates, a growing number of laboratories started in the eighties the investigation of μCF, namely JINR Dubna/Russia [18], PSI Villigen/Switzerland [19-23], LAMPF Los Alamos/USA, [24-27], PNPI Gatchina/Russia [28], KEK Tokyo/Japan [29], TRIUMF Vancouver/Canada [30] and RAL Chilton Didcot/UK [3 1]. The most extensive investigations of the *$d\mu t$ cycle* were done at the two meson factories LAMPF and PSI. At present, a quite consistent set of dt cycle rate results is available as shown in figs. 3(a,b). It shall be shortly discussed here:

(i) At low temperatures $d\mu t$ formation by reaction (1) is highly resonant (rate $\lambda_{d\mu t-d} \sim$ 4-108 see-l at density ϕ = 1.2 [20,24]) and strongly density dependent (fig. 4b). It is caused by the main resonance energy for D_2 molecules being negative. Therefore triple collisions μt + D_2 + D_2 cause the anomalous density dependence.

(ii) At higher temperature ($T > 300$K), both reaction channels (1) and (2) contribute significantly to $d\mu t$ formation [24].

(iii) All measurements at small tritium concentration ($c_t < 0.2$) indicate that the transfer cross sections $d\mu \rightarrow t\mu$ *are* not sensitive to density or to the type of molecules, see fig. 3(a). This is very surprising, since according to the present theories [32] the transfer rates from excited levels are expected to change strongly with density.

(iv) In dense dt-mixtures, the conditions for highest dt fusion yields XC were investigated. The following maxima were reported

	X_c (fusions/p)
S.E. Jones et al. 1986 [25] (in liquid D_2 + DT + T_2, ϕ = 1.2)	150 ± 20
W.H. Breunlich et al. 1987 [20] (in liquid D_2 + DT + T_2, 24 K, ϕ = 1.20)	113 ± 10
C. Petitjean et al. 1988 [21] (solid D_2 + T_2, 12 K, ϕ = 1.45)	124 ± 10

These yields do not present unsurmountable maxima, since at higher temperatures all kinetic rates are growing larger; but the technical conditions get harder, since very high pressures are needed. Sticking inverse (ω_s^{-1}) is in any case the theoretical limit to the fusion yield.

Fig. 4 shows the state of final sticking measurements ω_s, which is defined as the probability of remaining sticking, after the $(\mu^4\text{He})^+$ system with 3.5 MeV initial energy has come to rest. Final sticking is about 30 to 50 % lower than sticking immediately after $d\mu t$ fusion, since the muon can get shaken off during μHe slow down. There are significant discrepancies among the experimental data from different groups, and with respect to theory.

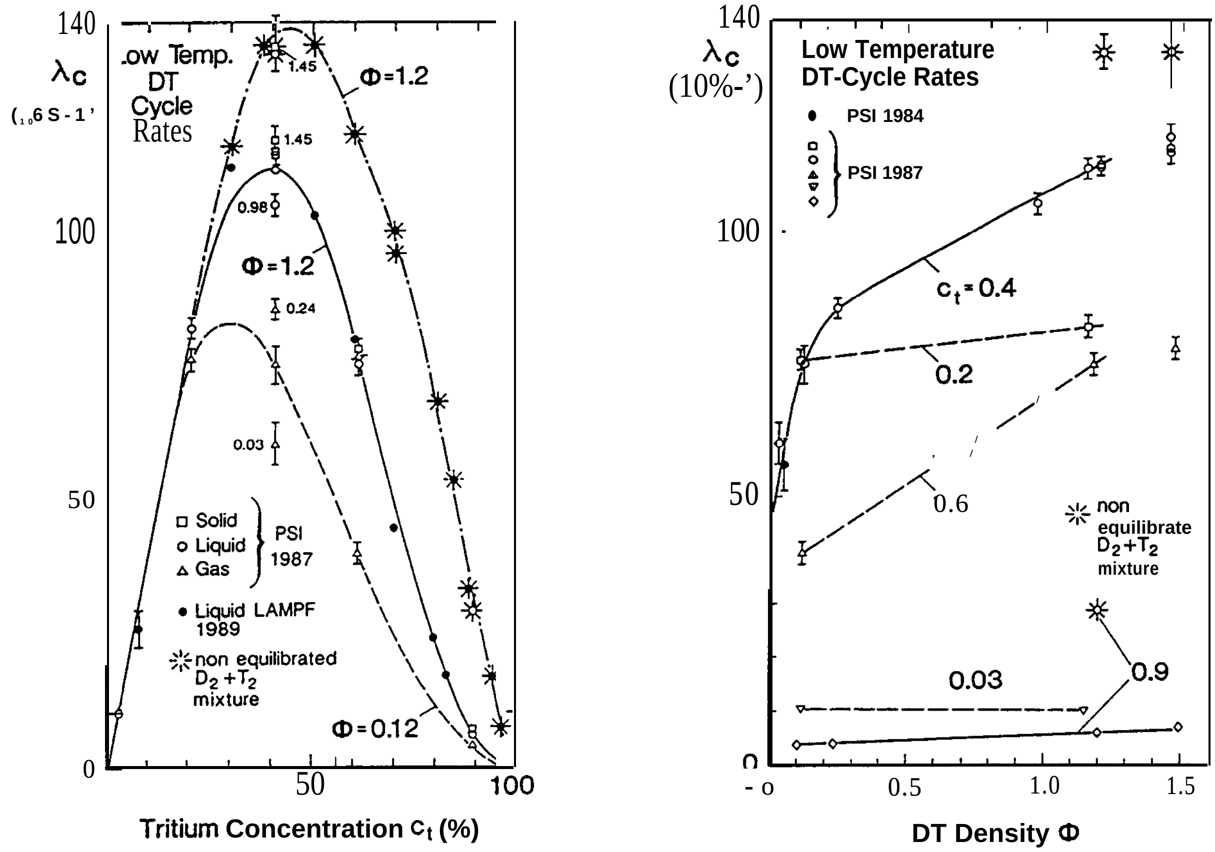

Figure 3: Overview of normalized dt cycle rates measured at temperatures 12K-35K (a) plotted versus c_t; the curves follow measurements of the same density in liquid mixtures $D_2 + T_2$ (dash-dotted curve), in liquid equilibrated mixtures $D_2 + DT +$ 2’$_2$ (full curve), and in equilibrated gas (dashed curve); (b) same data plotted versus dt density ϕ for various tritium concentrations ct.

A new effort was undertaken at PSI, to determine final sticking ω_s by observing the charged products of the dt fusion reaction directly in a special ionization chamber developed at the Petersburg Nuclear Physics Institute PNPI [28]. The preliminary results obtained in runs 1989 and 1991 for final sticking at density $\phi = 0.17$ are [23]

ω_s (expt.) = $(0.50 \pm 0.06)\ \%$ (run 1989, pressure 161 bar),

ω_s (expt.) = $(0.47 \pm 0.06)\ \%$ (run 1991, pressure 160 bar).

These results indicate lower sticking values than what the present theories predict ($\omega_s = 0.65 \pm 0.03$ % [33,34]). The new experimental values limit the fusion output per muon to 200.

Ways were considered how to overcome sticking. The most realistic method seems to be to enhance artificially muon reactivation, e.g. by acceleration of the $\mu\alpha$'s in electric or rf fields [35]. By another idea, it was shown that in high density plasma at certain conditions it may be possible to achieve $\sim 10^3$ μCF cycles per muon [36]. None of these schemes resulted so far in realizable projects. Quantitative artificial reactivation is a difficult task!

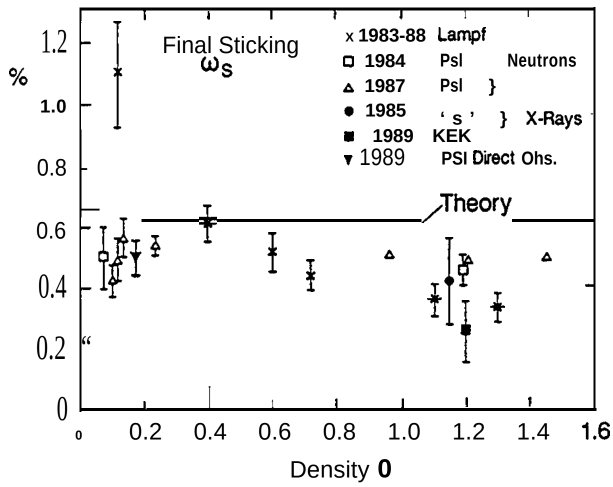

Figure 4: Plot of all experimental results on dt sticking ω_s versus density ϕ. The curve represents the theory [33,34] and shows a slight density dependence due to multistep excitations.

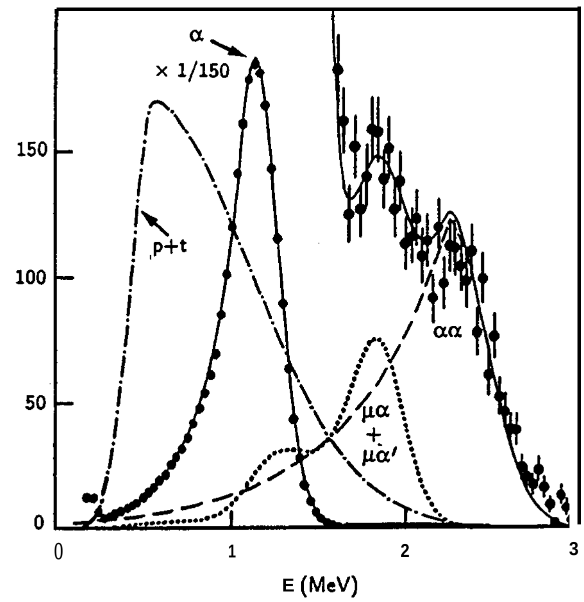

Figure 5: First direct measurement of final sticking ω_s at PSI, using the modular high pressure ionization chamber from PNPI [22,23,28]. The collected α and $\mu\alpha$ charges (energy) are separated by a recombination effect.

3. THE MUON CATALYZED HYBRID REACTOR (MCHR)

In 1978, immediately after the prediction of high rates for resonant alp-t formation, Yu.V. Petrov[17] suggested a scheme of practical application of μCF as follows:

A beam of deuterons (or tritons) from a high current accelerator comes to a target consisting of the light elements (Li,Be,C) where it produces in the optimal case $\approx 0.17\ \pi^-$ per 1 GeV_b incoming beam energy. After pion decay in flight $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$, one can collect with efficiency 0.75 [37] 0.13 μ^-/GeV_b and - assuming XC = 100 - produce 13 14-MeV neutrons/GeV_b. Every neutron can produce in an uranium-lithium blanket 0.86 fissions, 2.3 Pu nuclei and 0.7 tritium nuclei [38]. (0.6 tritium nuclei can additionally be produced via electronuclear channel). Considering that every Pu nucleus gives in a thermal reactor 1.7 fissions, the total output of electrical energy via μCF is 4.3 GeV/GeV_b. (The efficiency of transformation of thermal energy into electrical power was taken into account by the factor η = 0.40 for fast and η = ().34 for thermal reactors). Of the 4.3 GeV/GeV_b, ().9 GeV are from direct energy production and 3.4 GeV via breeding.

Only about 30% of the incident beam is spent for the pion production. The other 70% of accelerated nuclei can produce per 1 GeV_b in an uranium blanket 13 additional fissions and 45 Pu nuclei [38,39], i.e. 4.4 GeV/GeV_b.

In total, with one GeV beam power 8.7 GeV electrical power can be produced. Assuming an energy efficiency η = 0.6 for high current accelerators [17], the produced energy will approximately be four times the one spent, and the MCHR can produce nuclear fuel for 4 thermal nuclear reactors of the same power as the MCHR. This multiplication factor is one order of magnitude larger than what contemporary fast breeders provide.

For an MCHR with unit power 1 GW an accelerator with a beam power of $\approx$ 200 MW and a current of $\approx$ 100 mA (E_d = 2 GeV) is needed. The technical possibilities for the construction of such an accelerator are formidable, but conceivable. Thus, the main problem of MCHR's is not the principle, but are rather the cost, the special technological problems of tritium handling, the radiation damage of the dt containment and also the efficiency of the whole system in comparison with other schemes of nuclear breeding.[1]

4. INTENSE NEUTRON SOURCES

With todays knowledge about the $d\mu t$ cycle, μCF is definitively not energy productive by the direct production cycle. According to the presently known numbers about one order of magnitude is missing. But as long as no "hot" fusion mashines exist, μCF may offer the most economic way to provide intense 14 MeV neutron sources. The ratio of output energy of 14 MeV-neutrons (E_n) to accelerator input energy (E_{acc}) is:

(a) electrostatic 200 kV deuteron accelerator, to induce the dt reaction directly
- (see e.g. EC-project "Sorgentina" [40]): $(E_n/E_{acc}) \sim 10^{-5}$
(b) μCF (MHCR [17]) using a 2-4 GeV deuteron accelerator: $(E_n/E_{acc}) \sim 10^{-1}$

Even if a μCF neutron source is built in a simplified (less efficient, but cheaper) version as compared to Yu. Petrov's MCHR proposal, the advantage of method (b) is evident. Due to the much smaller input energy necessary for a projected output, the technological limits of achieving highest neutron fluxes are correspondingly higher. Such schemes are now being studied to assess the suitability as test facilities for materials research [41]. The ultimate goal would be a source strength of 10^{17} 14 MeV-n/s which would require a 10 mA / 2-4 GeV deuteron accelerator. An intermediate step with 3 orders of magnitude less beam power is considered to be already of interest.

[1] A very important preference of MCHR may be the possibility to enrich the depleted ^{238}U without chemical treatment (e.g. by making a blanket from it in order to prevent nuclear weapons proliferation.)

Independently, another application for intense neutron sources was studied by a Japanese-American collaboration: the burnup of nuclear waist by element transmutation [42]. The study follows closely the ideas outlined by Yu. Petrov [17]. Using rather optimistic assumptions about the effectiveness of the μCF cycle, it was shown that for burning ^{137}Cs, the μCF method would be a factor 4 superior to a spallation source. In the future a detailed study of the system as a whole has to be made in order to get a realistic assessment.

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