Contribution of Muon Catalyzed Fusion to Fusion Energy Development

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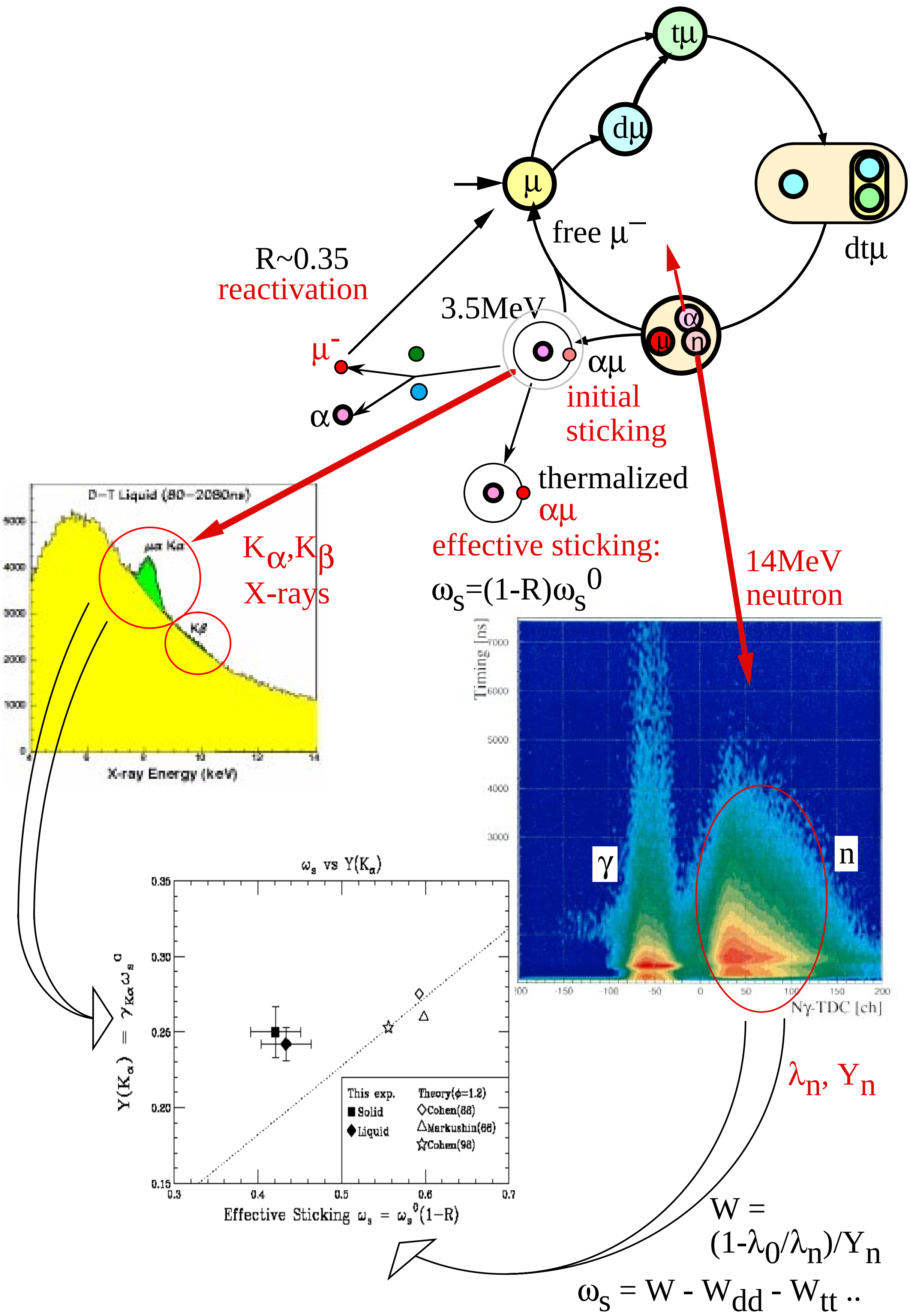
Abstract. Recent experimental studies on muon catalyzed fusion (μCF) process of D-T mixture have uncovered anomalously large muon (μ^-) regeneration from the $(\mu\alpha)^+$ stuck atom formed after nuclear fusion in dtμ-molecule. The result has opened a new direction towards a realization of the break-even. In addition, high-intensity hadron accelerator projects for neutron source etc. will realize kW μCF reactor once advanced muon generator be installed. Considering these new trends, we may be able to develop the fusion energy related R&D program based upon the μCF process such as materials irradiation facility, tritium breeding, fundamental plasma physics, etc.

1. Introduction

The basic process of the muon catalyzed fusion in D-T mixture as depicted in an upper part of Fig.1 can be summarized as follows.

After high-energy μ^- injection and stopping in a D-T mixture, either (dμ) or a (tμ) atom is formed, with a probability more or less proportional to the relative concentrations D and T. Because of the difference between (dμ) and (tμ) in the binding energies of their atomic states, μ^- in (dμ) undergoes a transfer reaction to t yielding (tμ) during a collision with the surrounding t in either D-T or T_2 molecules. The (tμ) thus formed reacts with D_2, DT or T_2 to form a muonic molecule at a rate of $\lambda_{dt\mu}$ followed by a fusion reaction occurring from a low-lying molecular state of the (dtμ) in which the distance between d and t is sufficiently close to allow fusion to take place a 14-MeV neutron and a 3.6-MeV α-particle are emitted. After the fusion reaction inside the (dtμ) molecule, most of the μ^- are liberated to participate in a second μCF cycle. There is however some small fraction of the μ^- which are captured by the recoiling positively charged α. The probability of forming an $(\alpha\mu)^+$ ion is called the initial sticking probability ω_s^0. Once the $(\alpha\mu)^+$ is formed, the μ^- can be stripped from the $(\alpha\mu)^+$ ion where it is "stuck" and liberated again. This process is called regeneration, with a corresponding fraction R. Thus, μ^- in the form of either a non-stuck μ^- or one regenerated from $(\alpha\mu)^+$ can participate in a second μCF cycle, leading to an effective sticking parameter ω_s: $\omega_s = (1\text{-}R)\ \omega_s^0$.



tμ
dμ
μ
free μ⁻
dtμ
R~0.35
reactivation
3.5MeV
μ⁻
α
αμ
initial
sticking
thermalized
αμ
effective sticking:
$\omega_s=(1-R)\omega_s^0$
14MeV
neutron
D-T Liquid (80-2080ns)
μα Kα
Kβ
X-ray Energy (keV)
K_α, K_β
X-rays
Timing [ns]
γ
n
Nγ-TDC [ch]
ω_s vs $Y(K_\alpha)$
$Y(K_\alpha) = \gamma_{K\alpha}\omega_s^a$
This exp.
Solid
Liquid
Theory(φ=1.2)
Cohen(88)
Markushin(88)
Cohen(98)
Effective Sticking $\omega_s = \omega_s^0(1-R)$
λ_n, Y_n
$W = (1-\lambda_0/\lambda_n)/Y_n$
$\omega_s = W - W_{dd} - W_{tt}$ ..

FIG.1. The μCF chain reaction together with details of the neutron and X-ray observables.

2. Recent μCF Experimental Results at RIKEN-RAL

In a series of recent experimental studies conducted at RIKEN-RAL muon facility, the strongest pulsed muon facility in the world by the RIKEN-KEK-JAERI-ETL-RAL group systematic measurements of both 14 MeV fusion neutrons and X-ray from the sticking phenomena from the μCF in high density (liquid/solid) and high T-concentration (10 – 70%) D-T mixture have been performed for the first time [1, 2, 3]. There, as shown in the lower part of Fig. 1, the following new insight has been obtained; the initial sticking mostly exhibiting in the associated X-ray intensity from the $(\mu\alpha)^+$ ion is rather consistent to the existing theoretical predictions while total sticking mostly exhibiting in a loss of the fusion neutron is substantially smaller, suggesting an existence of anomalous regeneration (ionization) process of the $(\mu\alpha)^+$ during a slowing-down collision in condensed D-T mixture. Further remarkable result has been obtained for the temperature dependent change in the observed phenomena; by changing temperature of solid D-T from 16 K down to 5 K, the observed anomaly becomes less prominent. The obtained result indicates by increasing temperature of solid D-T e.g. by applying a high pressure, one can attain a condition of the break-even. The experiment by using high pressure solid D-T target is now under preparation.

3. Towards Break-Even in μCF

In order to consider the energy-production efficiency, it is required to know how much energy is needed to produce a single muon (the muon cost). There have been several discussions on the optimization of the π^- production and $\pi^- \rightarrow \mu^-$ conversion processes. Using a 1 GeV/nucleon t(d) beam to bombard Li or Be nuclei, we can obtain 0.22(0.17) π^- from a single t(d). With the use of a large-scale superconducting solenoid with a reflecting mirror, one can expect 75 % efficiency for μ^- production from a single π^-. Since π^- production is proportional to the incident t(d) beam energy, and 1 GeV produces 0.17 μ^-, one μ^- per t(d) can be produced using an energy of 6(8) GeV. Selecting the values for π^- production in a t-t collision, the eventual cheapest cost might be about 1 π^-/4 GeV and 1 μ^-/5 GeV.

On the other hand, the energy-production capability $E_{\mu CF}^{out}$ of the μCF process is determined by $E_{\mu CF}^{out}$ = 17.6 x Y_n (MeV) in the case of D/T μCF, which has a stringent limiting factor due to the sticking probability ω_s ; this can be expressed $E_{\mu CF}^{out} \leq 17.6 \times \omega_s^{-1}$ (MeV). The situation in relation to $E_{\mu CF}^{out}$ is summarized in Fig. 2.

Several remarks can be made on the possibilities for a further increase in the energy-production capability of D/T μCF.

a) Since the conditions so far used for the D/T target in the μCF experiment such as density, temperature and C_t, as well as the energy of the (tμ) atoms $E_{t\mu}$, have not been satisfactory, there might exist more favorable conditions for higher energy production; one possibility would be a μCF experiment with a higher density D/T mixture on the order of $\phi \cong 2\phi_0$.

b) In order to increase $\lambda_{dt\mu}$, a more favorable matching condition in terms of resonant molecular formation may exist which might be accessed by exciting the molecular levels of D_2 or DT using e.g. lasers.

c) In order to decrease ω_s, or in order to increase R, several ideas have been proposed, among which the use of high pressure solid D-T seems to be promising according to the recent D-T experiment as indicated above.
d) Similarly, to increase R, the use of a D/T plasma where enhanced regeneration is expected due to an elongated $(\alpha\mu)^+$ mean-free path and acceleration of $(\mu\alpha)^+$ using an electric field are two that may be worth trying.
e) Due to collisions between the $(\alpha\mu)^+$ ions and α^{++} ions from nearby μCF reactions, exotic regeneration reactions may occur in high-density μCF in D/T mixtures with an intense μ^- beam. For this purpose it is indispensable to realize a very intense muon generator like the "super-super muon channel" [4]. With such a system, an intense muon of 2×10^{11} μ^-/s can be obtained with 25 MeV/c ≤ muon momentum ≤ 120 MeV/c. Using pulsed μ^- of this kind, muon catalyzed fusion phenomena with ultra-high fusion density can hypothetically be realized on a scale such as 3×10^{13} fusions/s in 5 liter target volume. The instantaneous μ^- intensity per unit volume of 2×10^8 μ^-/pulse/cc, which corresponds to a μCF density of 3×10^{10} μCF/pulse/cc, might be sufficient to yield interesting non-linear μCF phenomena. There, one might expect an enhanced regeneration of μ^- due to the spatially overlapping α-particles; $(\mu\alpha)^+(I)+\alpha^{++}(II) \rightarrow \mu^-+\alpha^{++}(I)+(\alpha)^{++}(II)$. This phenomena is similar to alpha-heating in thermal nuclear fusion.

	(GeV)	
0 ----		
100 ----	1.8	
		← μCF NEUTRON OBSERVED
200 ----		
		← STICKING PROBABILITY LIMIT
300 ----	5.3	← COST FOR μ^- PRODUCTION & SCIENTIFIC BREAK-EVEN
400 ----		
		↑
500 ----	8.8	μCF IN New (ϕ, T, C_T) LASER CONTROLLED μCF
600 ----		μCF IN PLASMA (αμ) ACCELERATION
700 ----		EXOTIC μCF
800 ----		↓
900 ----	15.8	ECONOMICAL BREAK-EVEN

FIG. 2. μCF number, energy output and remarks.

4. Contribution to Thermal Nuclear Fusion

A new accelerator project, like a spallation neutron source, neutrino factory, muon collider, etc. may contribute significantly to realize a kW level of the μCF reactor by employing the advanced muon generator as mentioned above. Considering these new trends of the μCF studies, one might expect a contribution of the μCF to the fusion energy development. The distinguished examples can be summarized as follows: 1) Materials development for the first wall of the fusion reactor… a high flux of 14 MeV neutrons at the level of 1 MW μCF reactor by using 1000 cc D-T mixture; 2) A tritium production test facility… by using high spatial density nature, the tritium breeding proposed for the fusion reactor can be more easily examined; 3) Contribution to studies of the plasma instability due to alpha-heating… a combination of the μCF process with the plasma facility can be used to the studies of selected aspects of the instability studies.

5. Conclusion

As a conclusion, the present status of the μCF studies is very close to a realization of break-even, e.g. (present) $150/\mu^-$, $\omega_s = 0.44$ %, R = 0.52, and (break-even) $300/\mu^-$, $\omega_s = 0.33$ %, R = 0.70. Consistent progress should be continued. Also, a realization of large scale D-T μCF experimental set-up should be achieved by employing high-intensity muon source at the forthcoming intense hadron accelerator. Such a set-up will be able to contribute a development of the fusion energy studies. In addition, a quick realization of constantly operational 0.1~1kW μCF fusion-reactor will be called for in order to obtain a support for the fusion energy from the individuals in the world.

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