Muon Catalyzed Fusion (μCF) - New progress and future plan

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Introduction

New progress

Muonic molecule formation with ortho/para D₂

Prospect with intense muon beam

in collaboration with

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What is muon catalyzed fusion (μCF)?

After injection of muons into D/T mixture (or other hydrogen isotopes)
  Formation of muonic atoms and muonic molecules
    nucleus-nucleus separation ~1/200 of normal atom
In small dtµ molecule, Coulomb barrier shrinks and d-t fusion
Muon released after d-t fusion
  - muon works as catalyst -
Exotic atoms and molecules
atomic physics in small scale
rich in few body physics problems
dt fusion and alpha-sticking
dtμ energy levels and formation
atomic collisions, muon transfer

Prospect for applications
(fusion energy, fusion neutron source)
uanon production cost (~5 GeV)
vs
fusion output (17.6 MeV x 120)
very close to breakeven
Maximizing $\mu$CF efficiency

Observables

1. Cycling rate $\lambda_c$ (↑) (vs $\lambda_0$: muon life)
   $dt\mu$ formation $t\mu + D2 \rightarrow [(dt\mu)dee]$

2. Muon loss per cycle $W$ (↓)
  Muon sticking to $\alpha$-particle is the main loss
  Transfer to $^3\text{He}$ is also important

Number of fusion per muon

$Y_n = \phi \frac{\lambda_c}{\lambda_n} = \frac{1}{[(\lambda_0/\phi \lambda_c) + W]}$ (↑)
Key process of μCF - dtμ formation

Auger formation: \(10^6 /s\) (as slow as muon decay rate \(0.45 \times 10^6 /s\))

\[ t_\mu + D_2 \rightarrow (dt_\mu) + D + e^- \]

Resonant molecular formation: \(10^6-10^9 /s\)

\[ t_\mu + D_2 \rightarrow ((dt_\mu) \text{ dee}) \]

(dtμ binding energy

\(\sim\) excitation of complex molecule)

(tµ energy to match the small
energy difference)

Thus,
large temperature dependence
dependence on initial states
(such as tµ spin state, D₂ states)

We could change (enhance) μCF by controlling initial D₂ states.
dtµ molecule formation
large formation rate (~10^9/s) by resonant formation mechanism
is established (temperature dependence, etc)
still many surprises 
non-trivial density dependence even after normalization 
three-body effect : tµ + D2 + D2' → ((dtµ)dee) + D2''
low temperature & solid state effect
φ dependence applies even to solid

![Graph showing Muon cycling rate vs density φ](image)
How about dd\(\mu\)?

Same resonant formation process applies for dd\(\mu\) formation in pure D\(_2\)

Slower compared to dt-\(\mu\)CF, and with lower energy output per fusion
Still, study should be done in parallel with study of dt\(\mu\)
   - No need of tritium
   - Simpler cycling process (pure D\(_2\))

\[d\mu + D_2 \rightarrow [(dd\mu)\text{dee}]\]

In analogy to dt\(\mu\) case,
   - temperature dependence
   - d\(\mu\) Hyperfine effect (\(F=1/2,3/2\))
   - D\(_2\) molecule effect
What has been known about ddμ formation

Resonant ddμ formation is nearly established in gas fitting by theoretical curve gives precision determination of shallow state binding energy in ddμ (-1.97 eV) which is comparable to the value by precise three-body calculation.

However, in liquid and solid, large deviation from theoretical curve.
Ortho- and para-$D_2$ in $\mu$CF

All the measurements so far were with normal $D_2$ (ortho:para = 2:1)
Thus, the resonance condition for ortho- and para- are mixed.

Ortho-$D_2$ (dd nuclear spin coupled with 0,2, $\psi_{\text{spin}} \psi_{J,v}$ symmetry under dd exchange
only $J=$even allowed)
Para-$D_2$ (simillary, for coupling with 1, $J=$odd allowed)

Resonance condition for each state should be separately measured.
Experimental setup @TRIUMF

ortho-D$_2$ and normal-D$_2$ preparation
ortho-para ratio analysis with Raman spectroscopy
Target cell (30cc liquid/solid, or 200cc pressurized gas)
muon beam counters B1+B2
me-decay electron counters E1-E8 (>50% solid angle)
neutron detectors(NE213) N1-N4
muon beam

gas preparation
D₂ target and detectors
Typical fusion neutron time spectra

fusion from resonantly formed dddu (b_{fast} component) was reduced in ortho-D_{2}
Result on ortho-para $D_2$ $\mu$CF

Normal $D_2$ and Ortho-$D_2$

Large effects (dd$\mu$ formation rate) were observed!

H. Imao(2004) in EXA-05, MSI-05 fusion neutrons]

Theoretical calculations agreed only with the gas result
(15% increase in ortho-$D_2$)
The effect was opposite to theory in liquid and solid $D_2$. 
To understand the result

For gas, the result was consistent with calculations based on idealistic non-interacting D₂

Inversion in liquid/solid is key to understanding effect of condensed matter in μCF

Theories are under development.

- energy shift, broadening
- (still it is difficult to change the order of resonance in ortho/para)
- phonon effect (solid only)

New experimental run with ortho- and para- D₂ for more temperature points (near liquid/gas boundary) is planned

共鳴位置とMaxwell分布

F=1/2

F=3/2

共振エネルギー[meV]
What about dtμ: theoretical calculations

1. Idealistic gas model
   \( tμ + D_2 \rightarrow [(dtμ)dee] \)
   low temp. resonance only for para-D\(_2\)

2. with Condensed matter effect
   under development [Adamczak]

   Even larger effect of ortho-para D\(_2\) expected!
Planned experiment and expected effect

Prepare ortho-D$_2$ and para-D$_2$ and mix with T$_2$

Enhancement or reduction of $\mu$CF in pure mixture followed by

1. molecular equilibration process
   \[ D_2 + T_2 \leftrightharpoons 2DT \text{ (~68 hour in D/T(50%)~)} \]
   \[ t\mu + D_2 \rightarrow [(dt\mu)\text{dee}] \]
   \[ t\mu + DT \rightarrow [(dt\mu)\text{tee}] (\lambda_{dt\mu}^{0,D2}>>\lambda_{dt\mu}^{0,DT}) \]

2. ortho-para equilibration by radiation effect
   o-p conversion by paramagnetic T atom
   ~16 hours in D/T(50%) at 14K

Cycling Rate
\[ \lambda_c = 1/(\tau_d + \tau_t) \]
\[ = 1/[q_{1s} C_d/\lambda_{dt} C_t] + (3/4)/(\lambda_{t\mu}^{1,0} C_t) + 1/(\lambda_{dt\mu-2D(\text{o,p})} C_{D2(\text{o,p})} + \lambda_{dt\mu}^{0,DT} C_{DT}) \]

av. time in t$\mu$(F=1) state

av. time before dt$\mu$ formation

av. time waiting d$\mu$-$t\mu$ transfer

\[ \lambda_c \quad \text{Ct = 0.50} \quad \lambda_0/\lambda_p = 0.01 \quad \text{equilibration time = 68 hr} \quad \text{op conversion time = 16 hr} \]
Towards highest fusion yield

$T_2$ mixture with ortho-$D_2$ at liquid/solid condition
best candidate for maximum fusion yield in $\mu$CF

1) Faster cycling rate
   high density $\phi$ (liquid, solid)
   faster $dt\mu$ formation rate
   $D_2$ para-rich (or ortho-rich)

2) Smaller $W$
   high density (liquid/solid) $\rightarrow$ high reactivation after $\mu\alpha$ sticking
   $W \sim 0.6\%$

Typical neutron yield in liquid D/T $\sim110$/muon
if $\lambda_c=260$

$$Y_n = \frac{\lambda_c}{\lambda_n} = 1/(\lambda_0/\phi\lambda_c + W) = 1/(0.45/1.25*260+0.006)=140$$
Preparation of ortho/para D$_2$ gas

Ortho D$_2$ (established)
  by ortho-para conversion with
  Al$_2$O$_3$/Cr$_2$O$_3$ catalysis

Analysis
  Raman scattering spectroscopy

Para D$_2$ (under study)
  selective absorption on Al$_2$O$_3$ at $\sim$20K
  99% para D$_2$ is possible

RIKEN-RAL Muon at ISIS (1994~)
Intense pulsed muon beam
(70ns width, 50 Hz)
800MeV x 200\(\mu\)A proton
20~150MeV/c \(\mu^+/\mu^-\) muon
5x10^4 \(\mu^-/s\) (55MeV/c)
µCF target and detectors

Cryogenic target: 1 c.c. liquid or solid D-T

Detectors with calibration
  fusion neutrons, X-rays, µe decay
  120 muon stops per pulse
  10^6 fusions/s
Other ongoing studies of μCF

Understanding mechanism and parameters of key processes
1. Muon-to-alpha sticking loss
   muon-to-alpha sticking x-rays
2. Muon loss to accumulated $^3$He from tritium decay
   $tHe\mu$ molecule formation and decay
3. dtμ formation in wider and exotic target conditions
   low temperature solid D/T, high density D/T, ortho-para D$_2$
4. fusion in ttμ
   particle correlations in $^4$He-n-n exit channel

Intense muon beams will definitely contribute to these study of μCF
1) efficient search of more and more target conditions
2) short-lived extreme conditions (laser, plasma etc)
3) better S/N
4) exotic beams from μCF
5) intense neutron source
Summary

A clear effect of ortho-para ratio was observed for dd$\mu$ formation in D$_2$, which is the most important rate limiting process in $\mu$CF.

Even larger effect (and enhancement) is predicted for dt$\mu$ formation.

This opens up possibility for enhancement of $\mu$CF by controlling initial molecular states.