GEANT4 Simulation Package for Interactions Related to MuonicAtom and Muon-Catalyzed Fusion (μCF)

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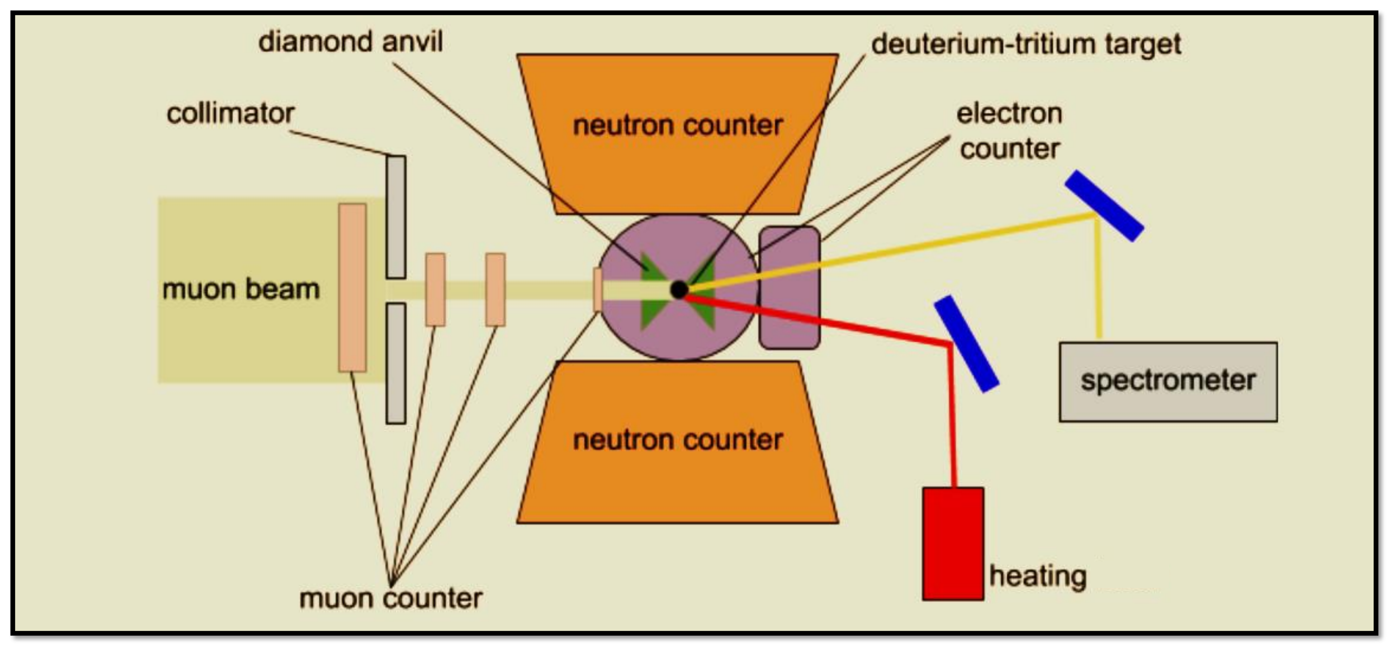
Introduction

- Muons, after getting stopped, form muonic atoms (***dμ, tμ***), which further produce diatomic muonic molecules (***ddμ, dtμ***).
- The larger mass of the muon in comparison to the electron reduces the molecular size, increasing the Coulomb screening between the nuclei and hence enhancing the nuclear wave function overlap and inducing a fusion event. Since the muon is not consumed in this reaction, it can go on to catalyze additional fusion events before it sticks to a helium nucleus with a probability called the initial sticking fraction (ω_s^0). However, there is a probability (***R***) it gets stripped from helium and returns to the fusion cycle. This way the effective sticking fraction becomes, ω_s^{eff}
- In this work, we report a simplified modeling of these Physics processes in GEANT4 [1], based on muon cycling rates for D:T=50:50 obtained following [2]. The muonic atom striping cross-sections are estimated by scaling the data of p-He collisions for muon's mass following the approach given in [3]. Simulation results for specific temperature and pressure have been provided.

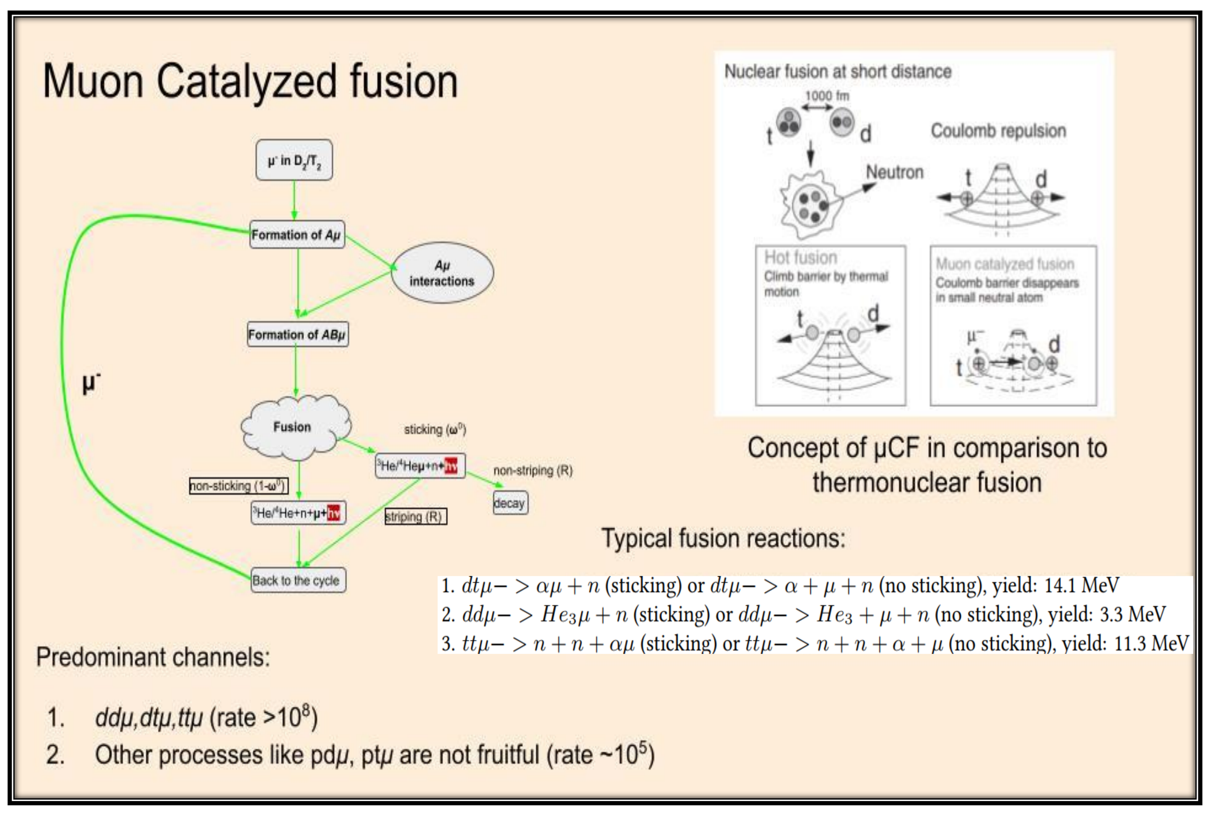
$$\omega_S^{\text{eff}} = \omega_S^0(1 - R) \qquad Y_{\text{f}} \simeq \left(\omega_S^{\text{eff}} + \lambda_0/\lambda_c\phi\right)^{-1}$$

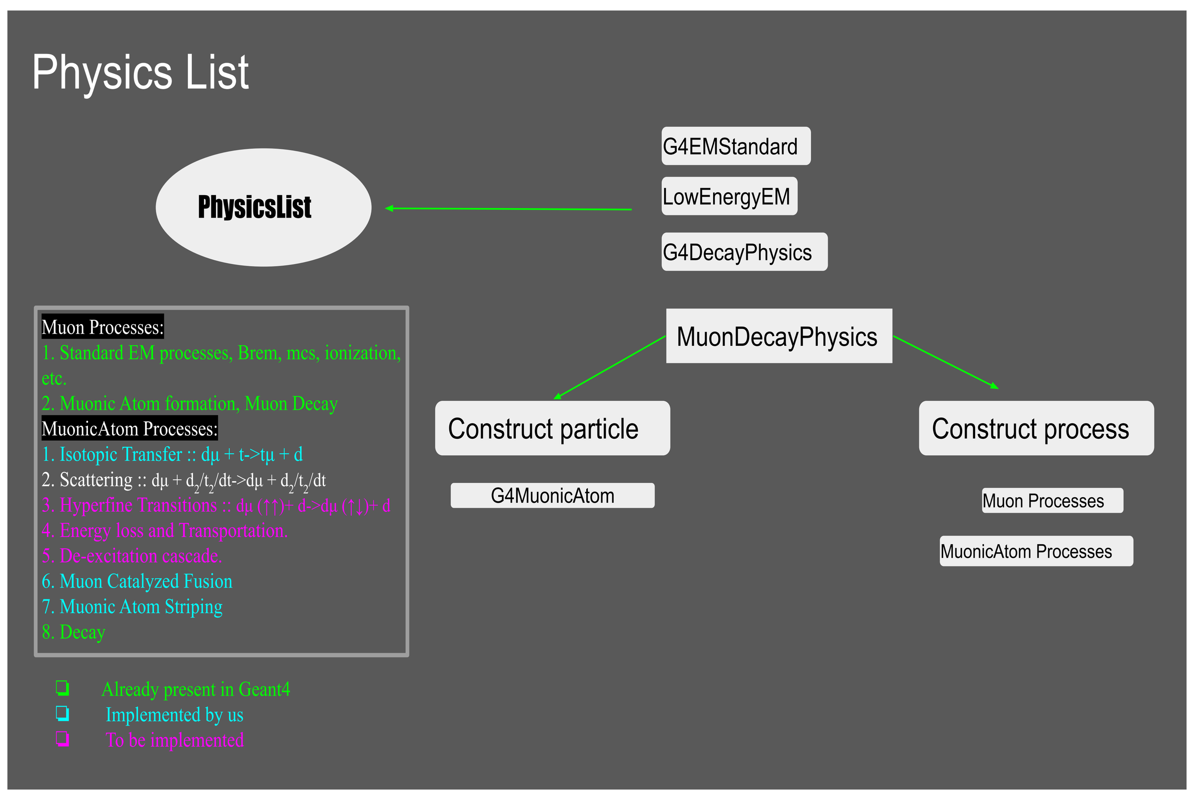
Here Y_f is the fusion yield, λ_0 is the muon life cycle, ***Φ*** is the target density wrt Liquid Hydrogen Density (LHD: 4.25e22 atoms cm^{-3}). λ_c is the average time between fusions, also called the muon cycling rate.

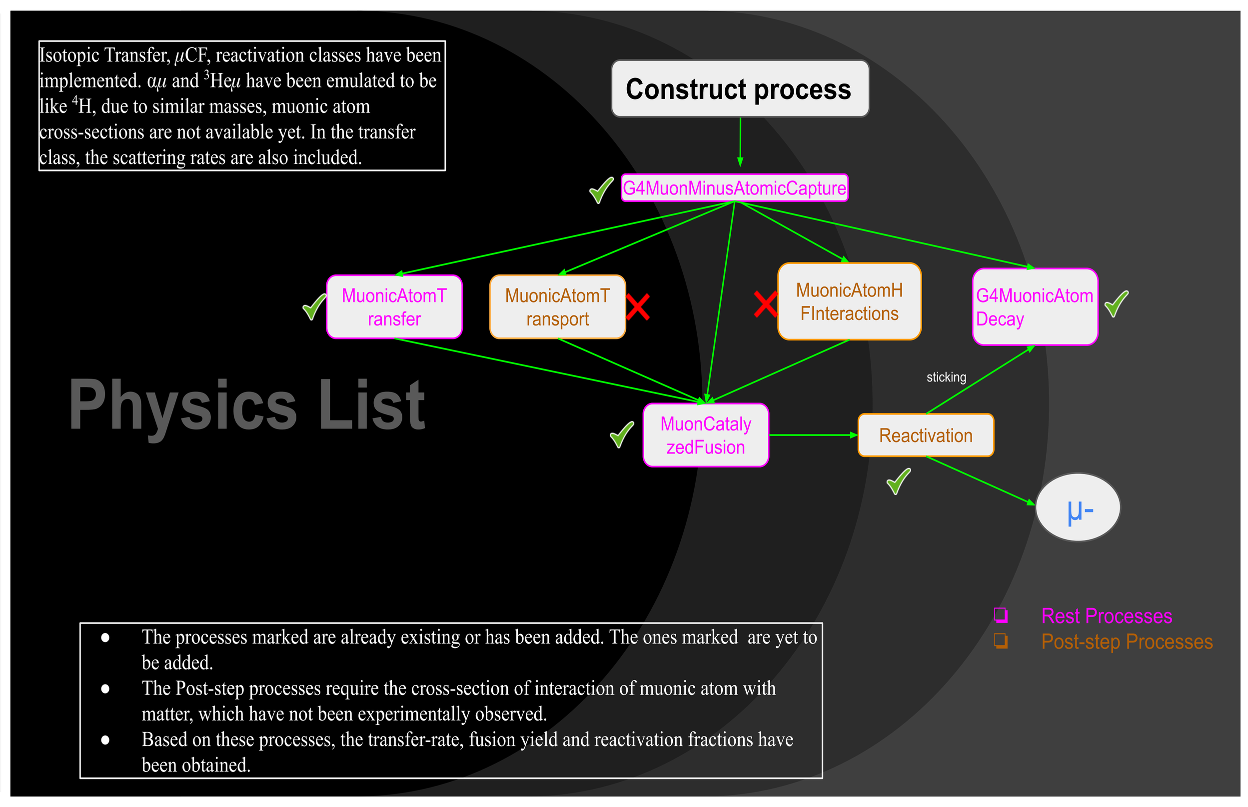
Experimental Setup for Testing Conditions for High-Yield Fusion

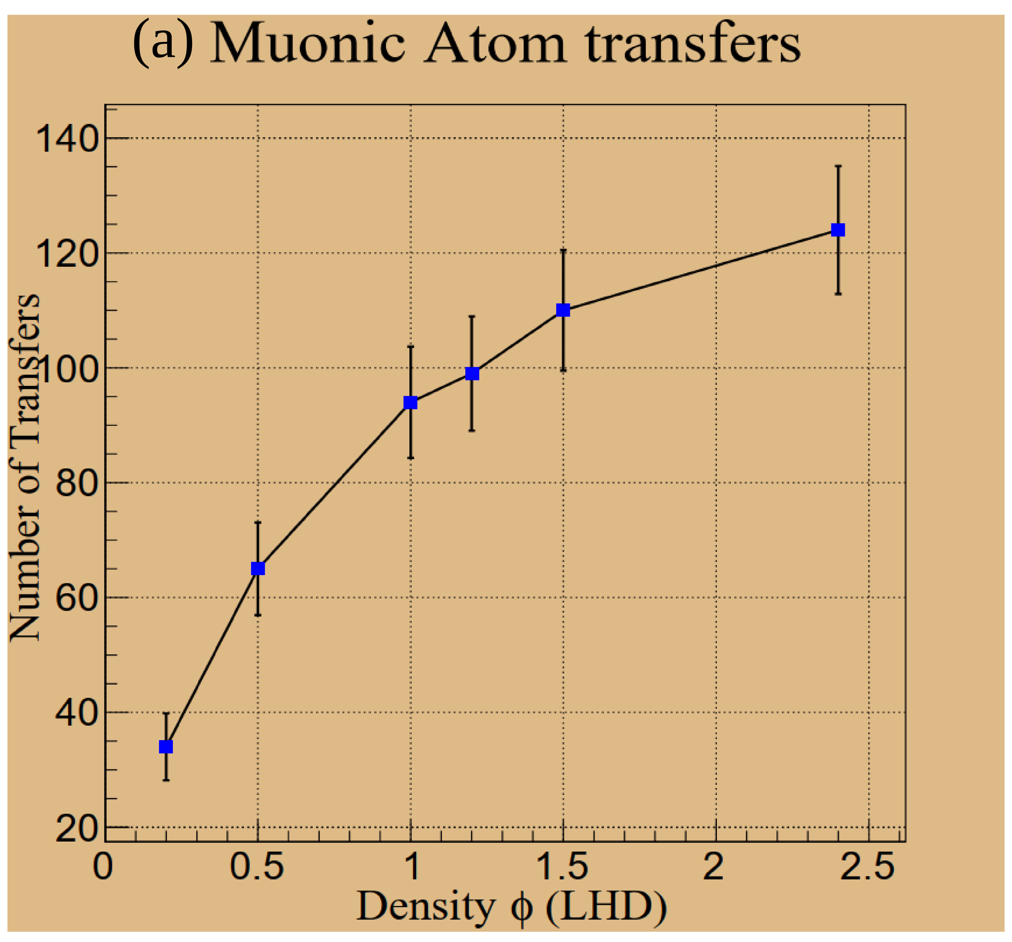


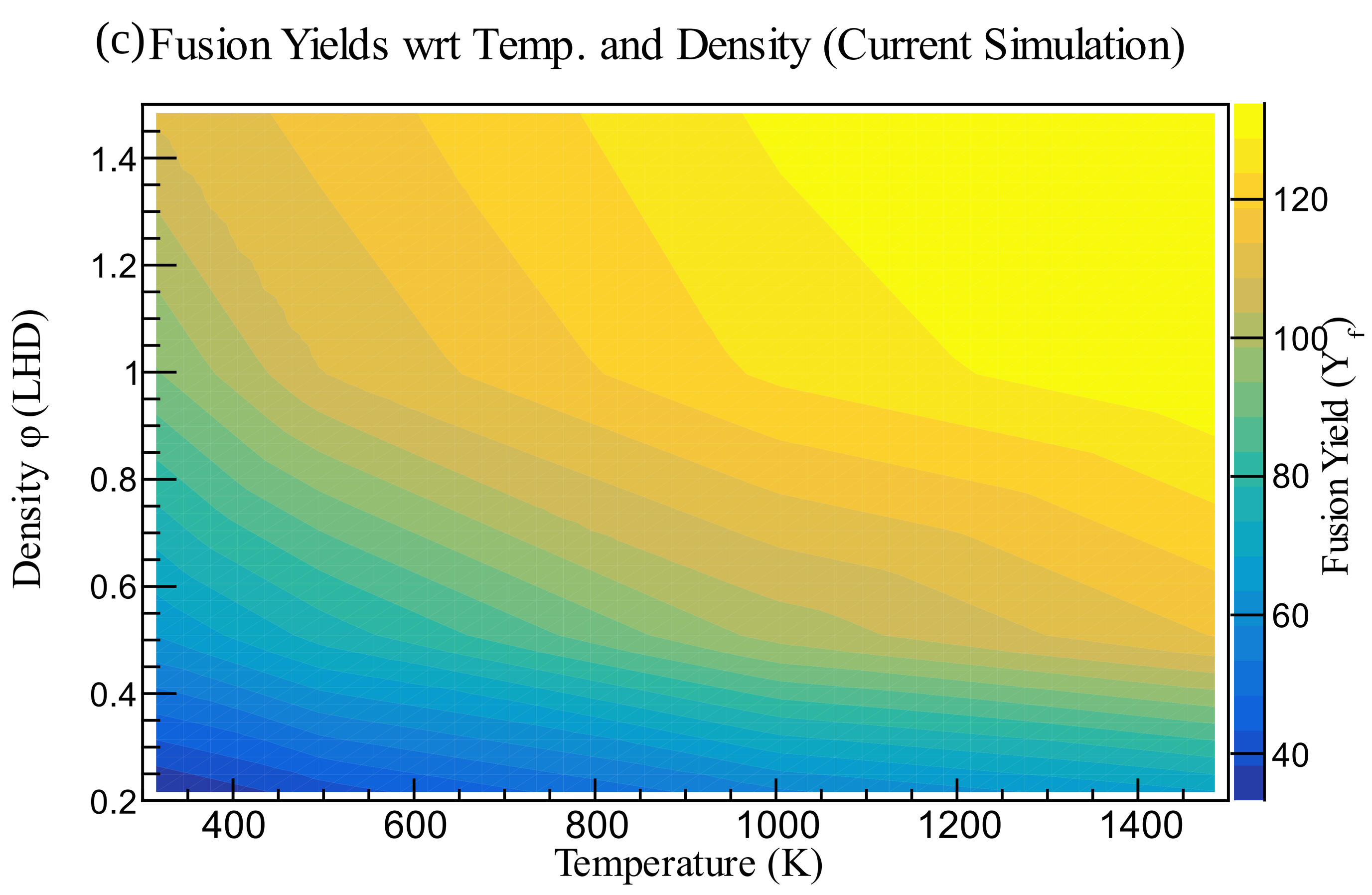
Schematic diagram depicting proposed experimental setup. The hydrogen isotope mixture (D/T) in diamond anvil cell is bombarded with muon beam. The goal is to study fusion yield for different pressure and temperature by detecting the neutrons produced due to ***μCF.***

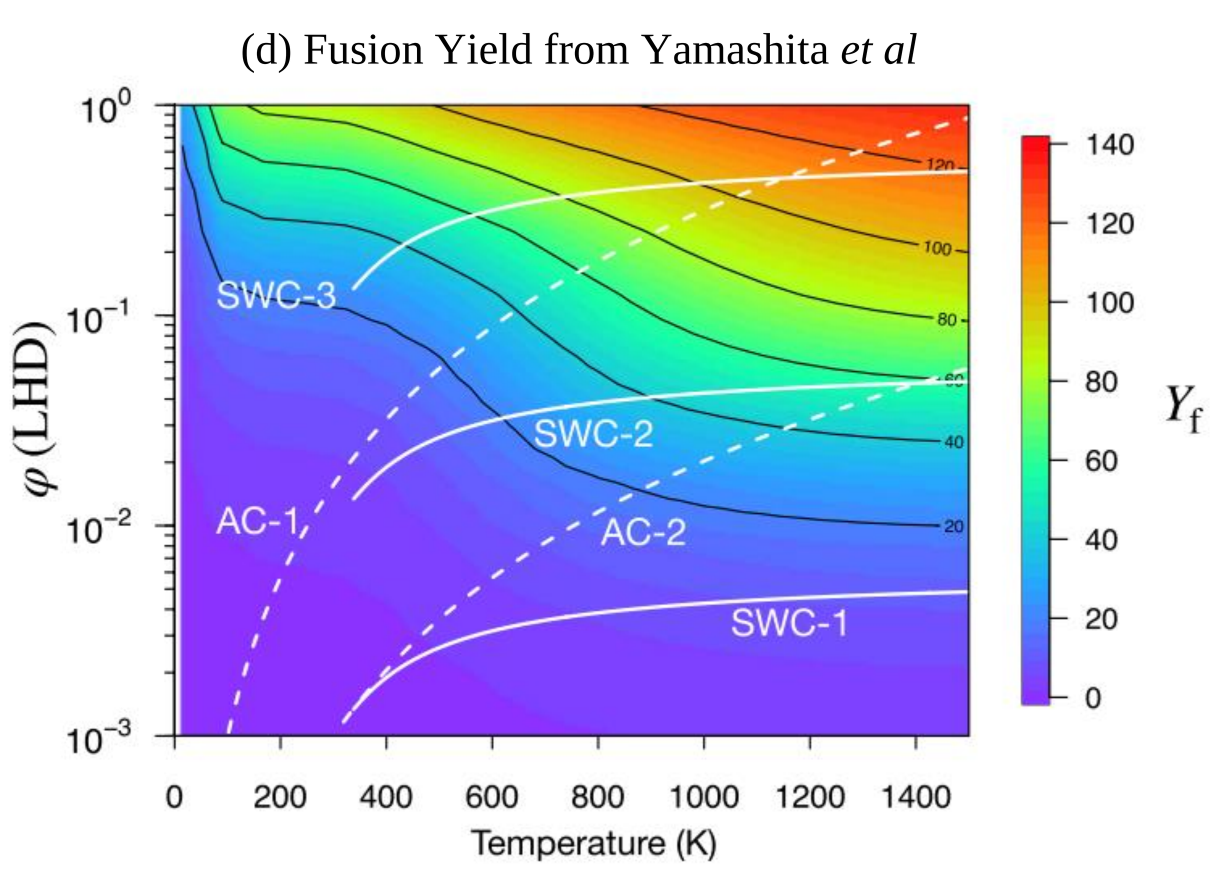


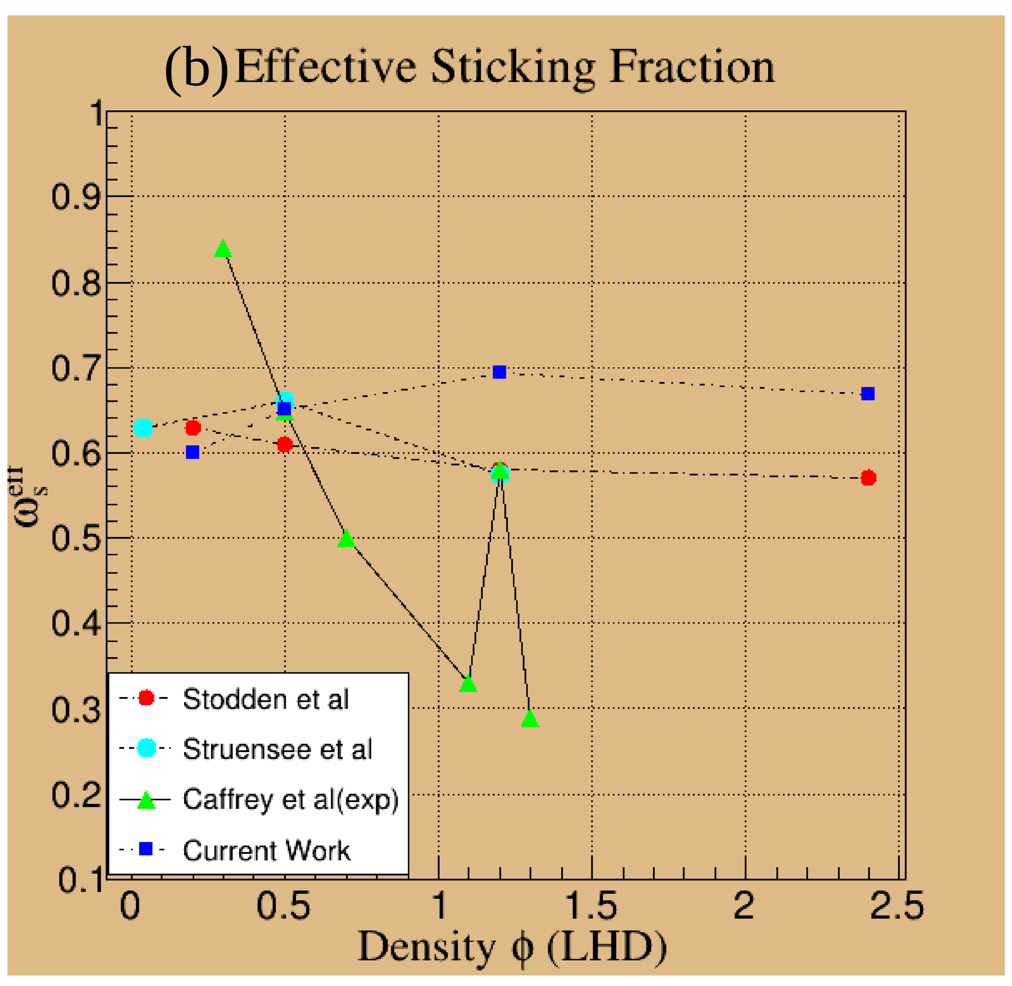












Discussion

(a) Muonic Atom Transfer rates as a function of ***Φ.*** With the increase in density the ***dμ -> tμ*** transfer rates rise.
(b) Effective Sticking Fraction (ω_s^{eff}) for different densities have been obtained. Published data from experiment [2], and calculations [3,4] have also been shown.
(c) Simulation results for fusion yields (Y_f) for different temperatures and densities.
(d) Results from Yamashita *et al.* [5] has been shown, obtained for relatively smaller densities.

Summary

- Different physics processes related to Muonic Atoms are being modelled in Geant4 based on the published studies. The goal of the simulation is to provide the experimenter comparable results to these studies.
- `MuonicAtomTransfer`, `MuonCatalyzedFusion`, and `MuonicAtomStriping` are some of the processes devised and integrated in the test code along with already existing muonic atom classes.
- Simulations are carried out for D:T = 50:50 mixture, rates for other concentrations of T are not implemented yet. The initial sticking fraction was considered to be 0.857% [6].
- The results form this elementary simulation are promising and can be improved by implementing, the cycling rates for tritium concentrations other than 50%, precise estimation of reactivation including striping for excited state, hyperfine transitions of muonic atoms, etc.
- The lack of muonic atom interaction cross-sections creates difficulty in implementing along-step/post-step reactions.
- The *dMu/DT* collaboration is studying the ***μCF*** rate and sticking fraction at a relatively higher temperature (but < 3×10^3 K) and pressure (but <10^5 bar), using a diamond anvil cell with D-T mixture

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