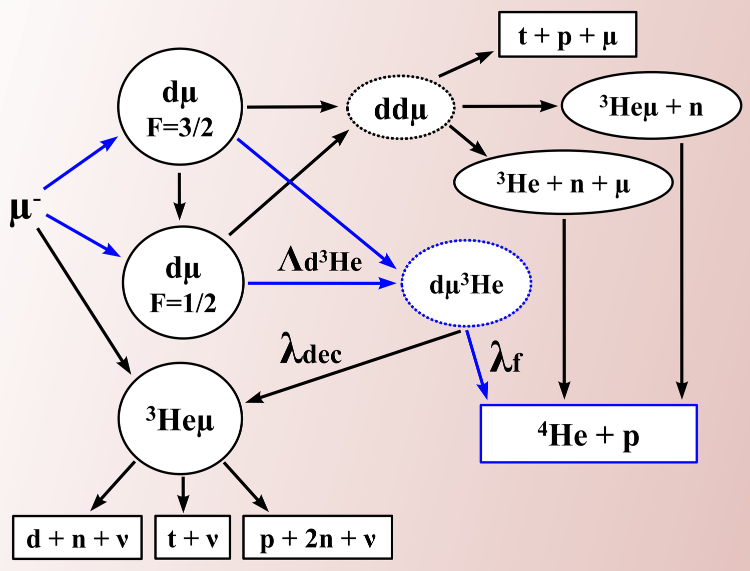

Search for muon catalyzed d^3He fusion

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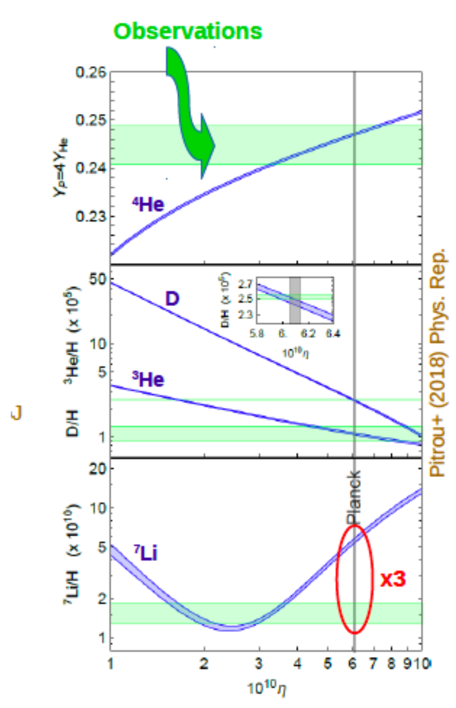
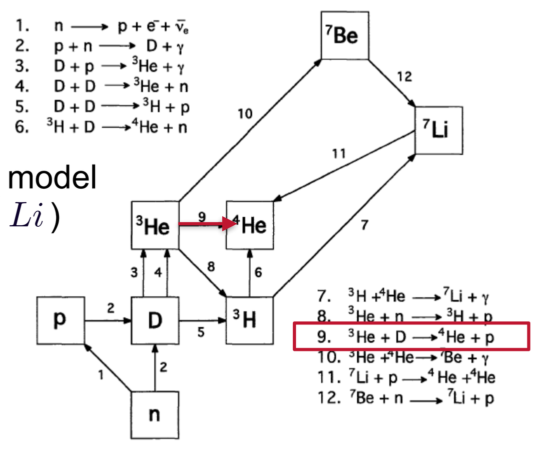
Motivation

The $d+^3He \to ^4He(3.66MeV) + p(14.64MeV)$ reaction plays a very important role[1] in

Primordial nucleosynthesis of the light elements.



According to the Standard Big Bang Nucleosynthesis model (SBBN) only the formation of light nuclei ($^2H, ^{3,4}He, ^7Li$) is predicted in observable quantities, starting from protons and neutrons [2].



Today, with the only exception of ^3He and lithium, the abundances of these isotopes are rather consistent with SBBN predictions.
(still unsolved astrophysical problem so called **"Lithium depletion"** either in the Sun or in other galactic stars.)

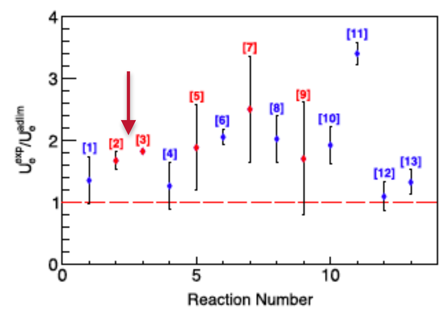
For experimentally studying the electron screening effect [3]

Table 1
The experimental values of the electron screening potentials, U_e^{exp}, and theoretical adiabatic limits, U_e^{adlim}.

	Reaction	U_e^{adlim} (eV)	U_e^{exp} (eV)	Note	Ref.
[1]	$^2H(d,t)^1H$	14	19.1±3.4		[16,17]
[2]	$^3He(d,p)^4He$	65	109±9	D_2 gas target	[18]
[3]	$^3He(d,p)^4He$	120	219±7		[18]
[4]	$^3He(^3He,2p)^4He$	240	305±90	compilation	[2]
[5]	$^6Li(d,\alpha)^4He$	175	330±120	H gas target	[19]
[6]	$^6Li(d,\alpha)^4He$	175	330±49		[19,20]
[7]	$^6Li(p,\alpha)^3He$	175	440±150	H gas target	[19]
[8]	$^6Li(p,\alpha)^3He$	175	355±67		[19,21,22]
[9]	$^7Li(p,\alpha)^4He$	175	300±160	H gas target	[19]
[10]	$^7Li(p,\alpha)^4He$	175	363±52		[19,21,23]
[11]	$^9Be(p,\alpha_0)^6Li$	240	788±70		[24,25]
[12]	$^{10}B(p,\alpha_0)^7$	340	376±75		[26,27]
[13]	$^{11}B(p,\alpha_0)^8Be$	340	447±67		[26,28]

To understand the energy production in stars an accurate knowledge of nuclear reaction cross section $\sigma(E)$ close to the Gamow energy E_G is required.
The experiments need to include an effective "screening" potential to explain the enhancement of the cross section at the lowest measurable energies.

A theory has not been found that can explain the cause of the exceedingly high values of the screening potential needed to explain the data.
(**"Electron screening puzzle"**)



Global R-matrix analysis of the ^5Li system

Key ingredient is the thermonuclear reaction rate

$$r_{xy} = N_x \cdot N_y \cdot v \cdot \sigma(v)$$

The calculation of the reaction rates relies on the cross sections [4]. There are two main problems in nuclear astrophysics:
(i) the stellar energies being much smaller than the Coulomb barrier, the relevant cross sections between charged particles are too small to be measured in the laboratory;
(ii) explosive burning involves short-live nuclei which, even if they can be produced with modern technologies, are available with weak intensities only.
Consequently a theoretical support is necessary, either **to extrapolate** the cross sections down to astrophysical energies, or **to predict** unknown cross sections.

$$\langle \sigma v \rangle = \left(\frac{8}{\pi m}\right)^{1/2} \frac{1}{(kT)^{3/2}} S(E_0) \int_0^\infty exp\left(-\frac{E}{kT} - \frac{b}{\sqrt{E}}\right) dE$$

Theoretical methods: Many different cases, but no "unique" model!

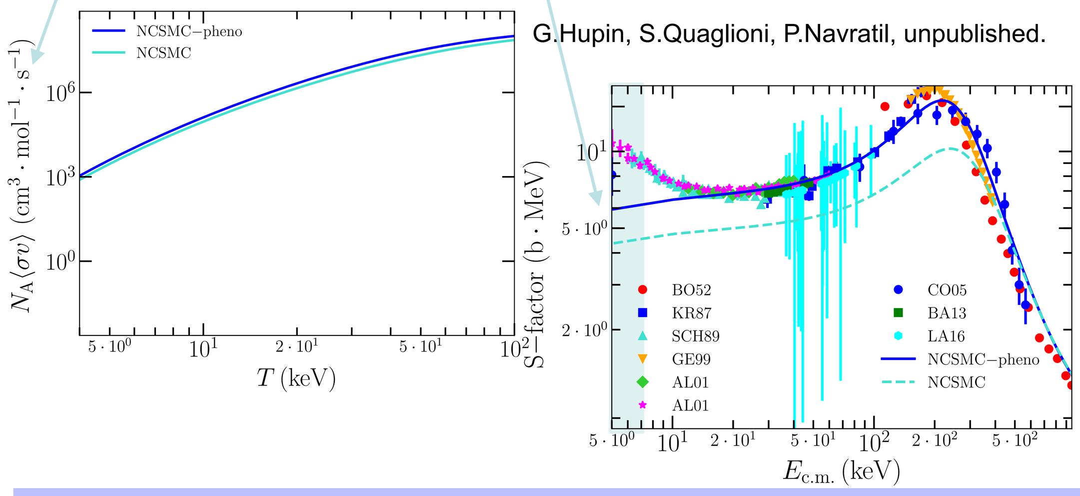
Model	Applicable to	Comments	
Potential/optical model	Capture Fusion	• Internal structure neglected • Antisymetrization approximated	Light systems Low level densities
R-matrix	Capture Transfer	• No explicit wave functions • Physics simulated by some parameters	
DWBA	Transfer	• Perturbation method • Wave functions in the entrance and exit channels	
Microscopic models	Capture Transfer	• Based on a nucleon-nucleon interaction • A-nucleon problems • Predictive power	

Cluster models
- In general a good approximation, but do not allow the use of realistic NN interactions
- Example: α particle described by 4 0s orbitals
  → intrinsic spin =0
  → no spin-orbit, no tensor force, no 3-body force
  → these terms are simulated by (central) NN interactions

Ab initio models
- No cluster approximation
- Use of realistic NN interactions (fitted on deuteron, NN phase shifts, etc.)
- Application: d+d systems $^2H(d,\gamma)^4He$, $^2H(d,p)^3H$, $^2H(d,n)^3He$
  two physics issues
  - Analysis of the d+d S factors (Big-Bang nucleosynthesis)
  - Role of the tensor force in $^2H(d,\gamma)^4He$

Ab Initio Many-Body calculations of the $^3He(d,p)^4He$ fusion reaction

G.Hupin, S.Quaglioni, P.Navratil, unpublished.



Excellent characteristics for use in the determination of the tensor polarization of deuteron beams

Muon catalyzed Fusion

muCF provides a unique method to study these nuclear few-body reactions: in muonic molecules the two nuclei can be prepared in selected states of total spin I and nuclear fusion occurs at extremely low collision energies.

$$^3Hed\mu \to ^4He(3.66MeV) + p(14.64MeV) + \mu$$

Formation in collisions of slow atoms [6]

$$d\mu + ^3He \xrightarrow{\lambda_f^J} (^3Hed\mu)_J$$

predicted as an intermediate step in the muon transfer from the deuterium mesoatom to the helium atom

$$\lambda_{d^3He} = 1.48 \cdot 10^8 \ s^{-1}$$ confirmed PNPI -1984,1992 PNPI-PSI-1999

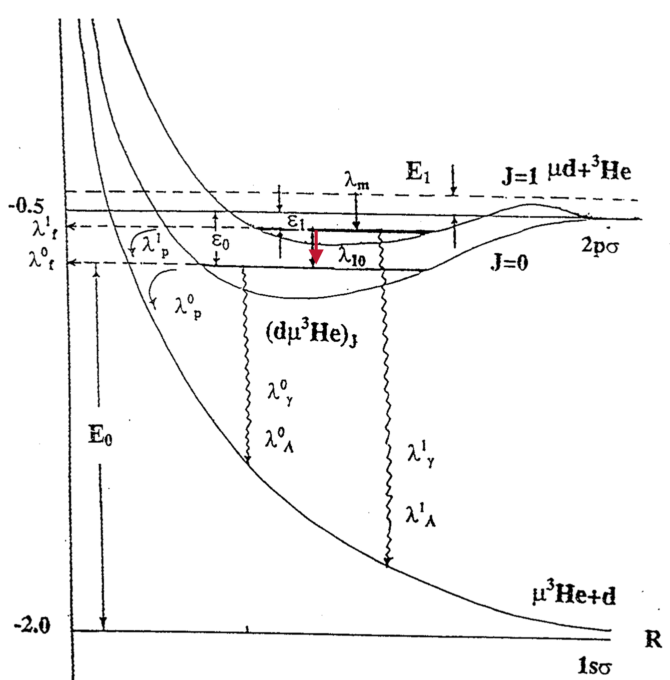
Decay

- by γ-emission $(^3Hed\mu)_J \xrightarrow{\lambda_\gamma} (\mu^3He)_{1s} + d + \gamma$
- Auger transition $(^3Hed\mu)_J \xrightarrow{\lambda_A} (\mu^3He)_{1s} + d + e$
- predissociation $(^3Hed\mu)_J \xrightarrow{\lambda_p} (\mu^3He)_{1s} + d$

Transitions $(J=1) \to (J=0)$

with the rate λ_{10} are possible

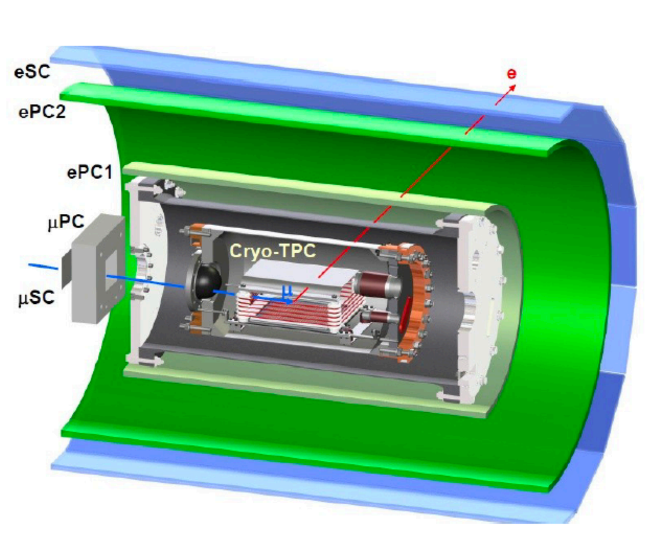
$$(d\mu^3He)_{J=1} \to (d\mu^3He)_{J=0}$$



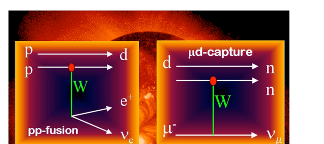
as a consequence
a detectable $d\mu^3He$ nuclear fusion [7]
with the rate $\lambda_f = P_0 \lambda_f^0 + P_1 \lambda_f^1$

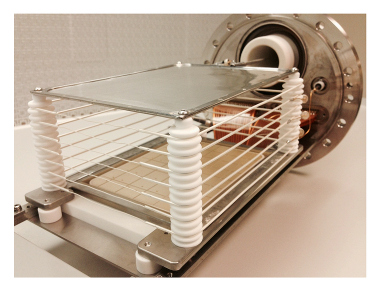
Experimental setup

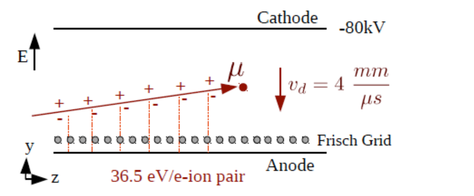
The main goal of **MuSun** is measurement of the muon capture rate in deuterium.

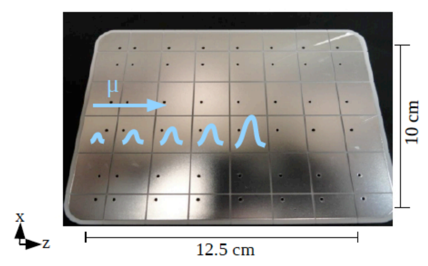


The incoming muons are detected first by a thin scintillator counter SC and by a wire proportional chamber PC. Then they pass through a 0.4 mm thick hemispheric beryllium window and stop in the sensitive volume of the time-projection chamber, TPC.



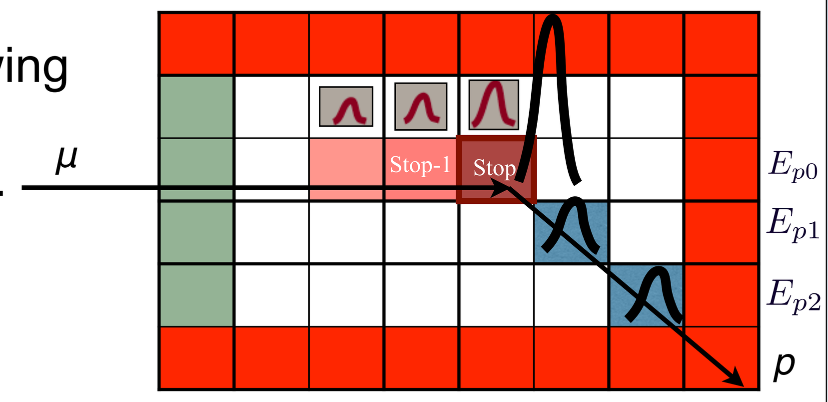






The TPC is the **key element** of the experimental setup.
It is filled with ultra-pure protium-depleted deuterium gas at the temperature T = 31 K and pressure P = 5 bar, and it operates as an active target in the ionization grid chamber mode (without gas amplification). Its main goal is to select the muon stops within the fiducial volume of the TPC well isolated from the chamber materials.

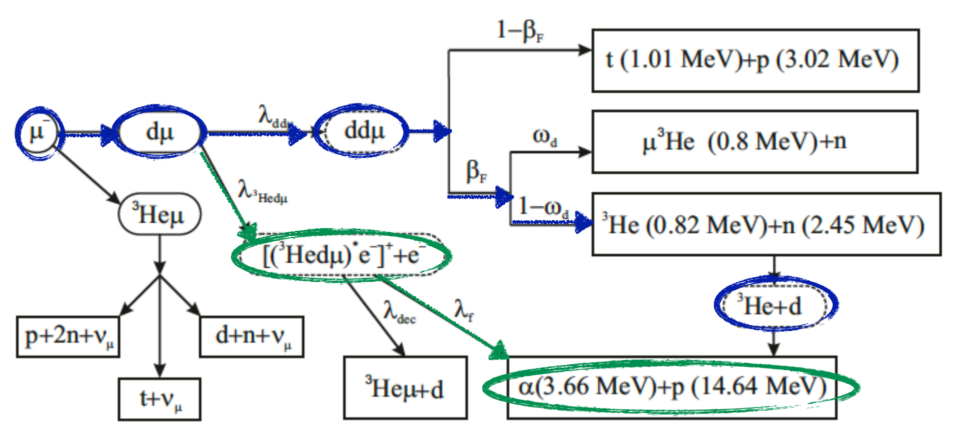
TPC detects products of reactions following the muon stop, including products of the d^3He fusion.



Data Analysis

$^3He + d$ fusion-in-flight

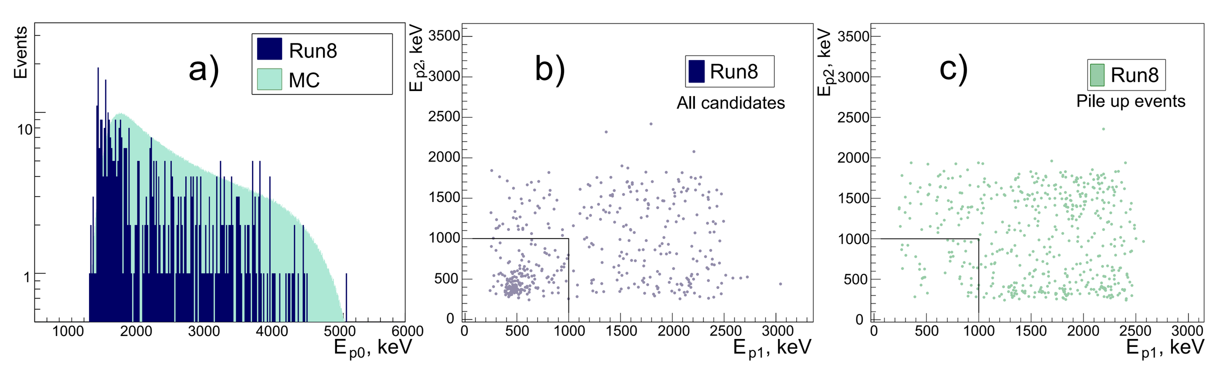
$$dd\mu \to d + ^3He(0.82MeV) \to ^4He(3.66MeV) + p(14.64MeV)$$



1.3·1010 decays of the muons stopped in the sensitive volume of the MuSun active target **with ultra clean** D_2 **gas** were registered in **Run 8** (2015) of this experiment.

The main background comes from collisions with D_2 of the ^3He (0.82 MeV) nuclei produced in the dd fusion reaction.

Run	Gas filling	Temperature	Pressure	D_2 density, C_d	Gas purity
Run 8	D_2	$31\ K$	$5\ bar$	6.5% LHD	$< 2 \cdot 10^{-9}(N_2)$
Run 9	$D_2 + 5\%^3He$	$31\ K$	$5\ bar$	6.2% LHD	$< 2 \cdot 10^{-9}(N_2)$



Muon catalyzed $^3He + d$ fusion

$$^3Hed\mu \to ^4He(3.66MeV) + p(14.64MeV) + \mu$$

The MuSun collaboration has performed an additional **Run 9** (2016) with the active target filled with the $D_2 + ^3He$ (5%) gas mixture, keeping all experimental conditions identical to those in Run 8.

Results

run	μ	Weeks	Ntot	NFinF/
Run8	1.3E+10	9	99	77/22
Run9	1.0E+09	1	2	1.9/0.34

$$\lambda_f = N_f \cdot \lambda_{dec} / N_{^3Hed\mu} \cdot \epsilon_f$$

$\lambda_{dec} = 7 \cdot 10^{11}\ s^{-1}$ decay rates

$N_{d\mu^3He} = 1.4 \cdot 10^8$ number of produced $d\mu^3He$ molecules

$\epsilon_f = 0.30$ registration efficiency

upper limit for the effective muon catalyzed d^3He fusion rate

$$\lambda_f \leq 6.3 \cdot 10^4\ s^{-1}\ at\ 90\% C.L.$$

in a good agreement ! [8] $\lambda_f < 6 \cdot 10^4\ s^{-1}$

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