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HIGH PRECISION STUDY OF MUON CATALYZED FUSION IN D_2 AND HD GASES

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During $1994 \div 1996$, a series of muon catalyzed fusion (μCF) experiments was performed in a high intensity muon beam at PSI by the PSI-PNPI-IMEP-LBNL-TUM collaboration. These experiments aimed at detailed studies of the muon catalyzed dd fusion (dμd fusion) in D_2 and HD gases. A time-projection hydrogen ionization chamber was used to detect the muon stops and the dd fusion reaction products. The applied experimental technique allowed to determine with high absolute precision the major parameters of the processes involved in the dμd fusion. This report presents the results of final analysis of the experimental data. The obtained results are compared with calculations based on recent μCF theories.

Brief History

1937	Anderson&Neddermeyer	discovery of μ
1947	Frank	idea of μCF
	$pd\mu \rightarrow He + \mu(5.3\ MeV)$	vs. $\pi \rightarrow \mu(4.2\ MeV) + \nu$ (Lattes, Occhialini, Powell)
1948	Sakarov	physics model and energy production
1957	Alvarez et al.	experimental discovery
1957	Jackson	efficieny of catalysis
1966	Dzhelepov et al.	temperature dependence of ddμ formation
1967	Vesman	resonance mechanism proposed
1977	Ponomarev et al.	quantitative predictions ddμ, dtμ
1979	Bystritski et al.	$\lambda_{dt\mu} \approx 10^8\ s^{-1}$
	worldwide effort	≈ 150 fusions/μ, ≈ 2.5 GeV/μ

ddμ model case for resonance mechanism

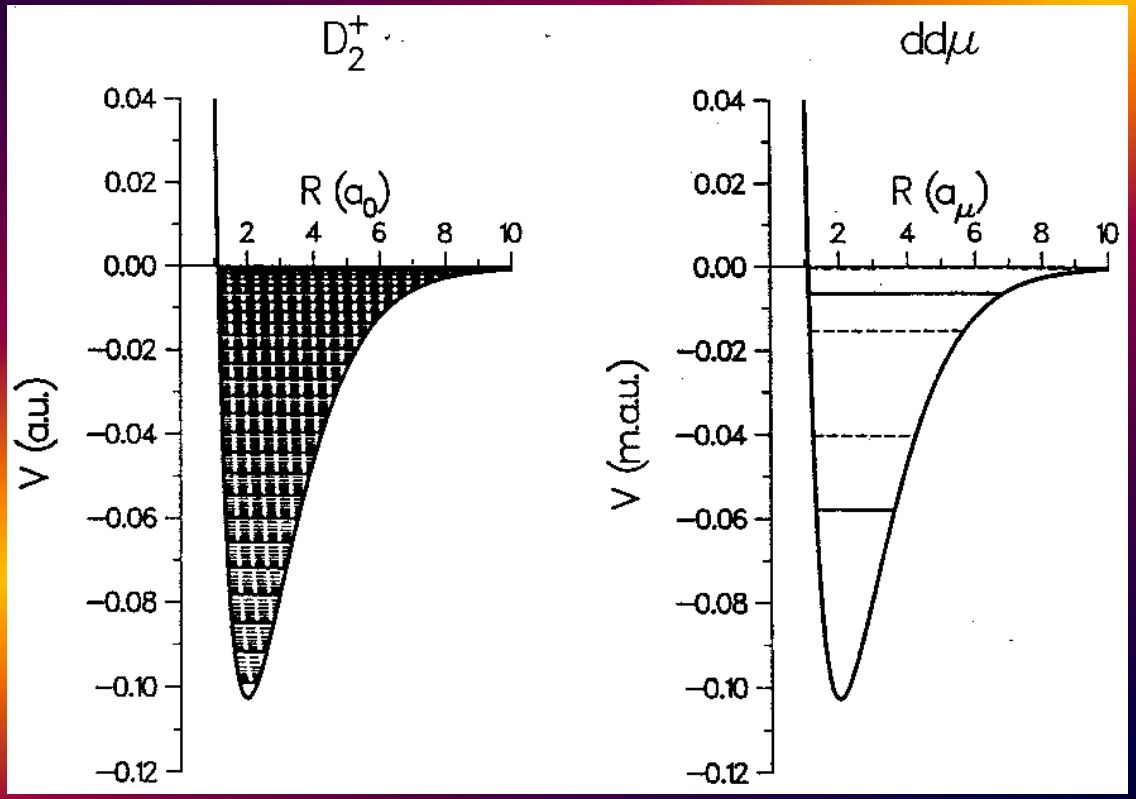
1979	Kammel et al.	discovery of hyperfine effects
	....	
2007	Balin et al.	final analysis of 1994-1996 PSI-PNPI-IMEP-LBNL-TUM

Resonance mechanism

$$d\mu + D_2 \rightarrow [dd\mu, de]^+ + e^-$$

$$d\mu + D_2 \rightarrow [dd\mu, dee]^*$$

Gift of Nature



Hyperfine effects

$dd\mu \rightarrow {}^3He + \mu + n$ (3.27 MeV)

FIRST OBSERVATION OF HYPERFINE TRANSITIONS IN MUONIC DEUTERIUM ATOMS VIA RESONANT dμd FORMATION AT 34 K☆

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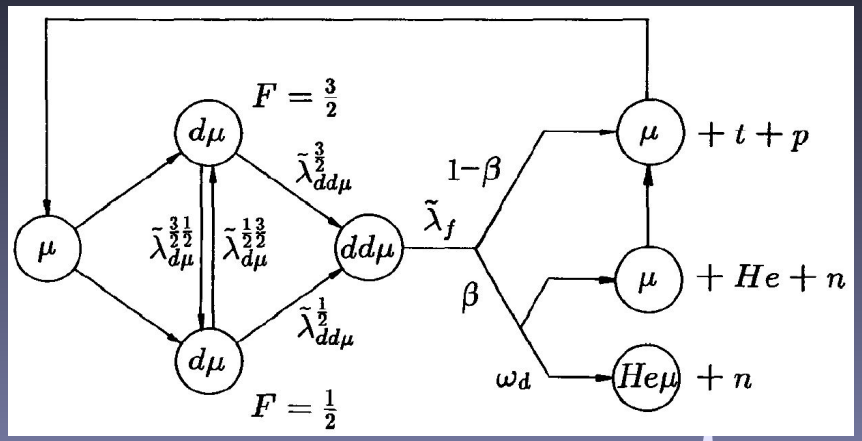
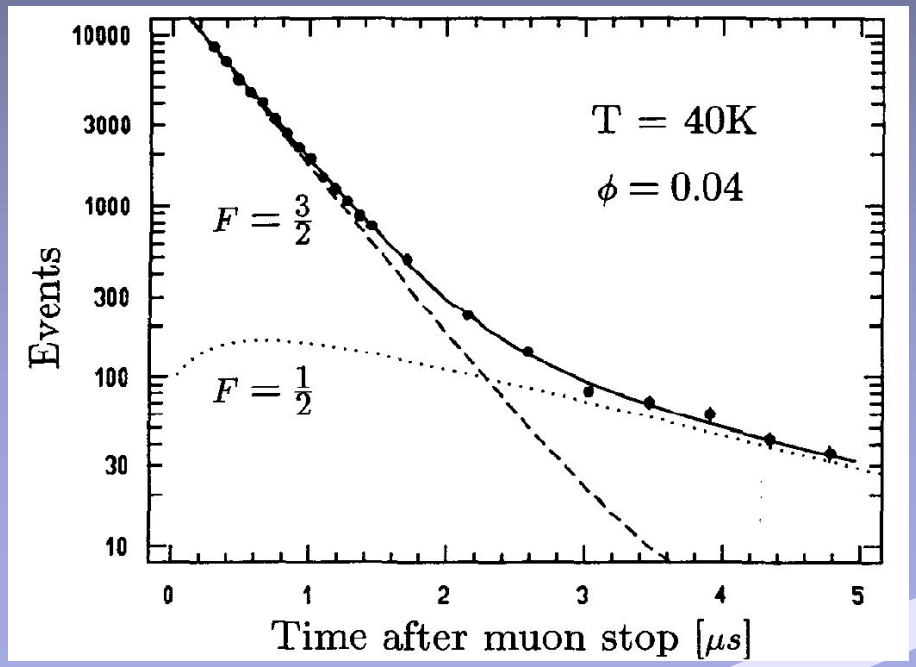
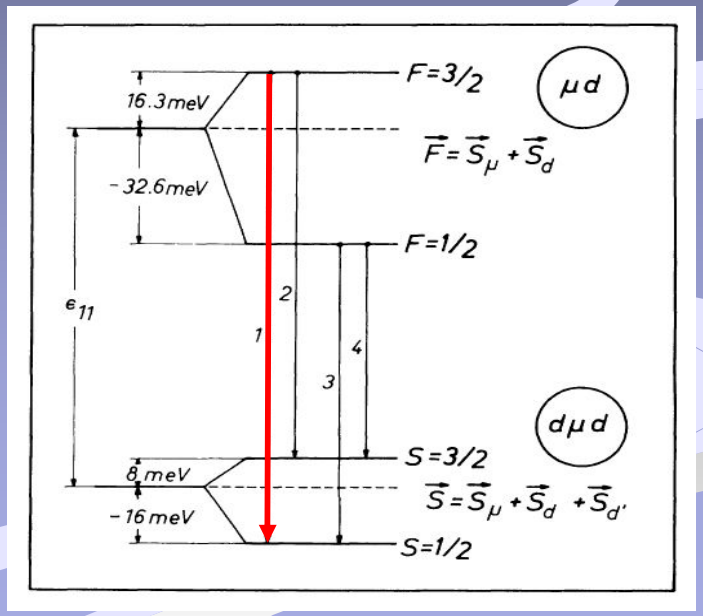
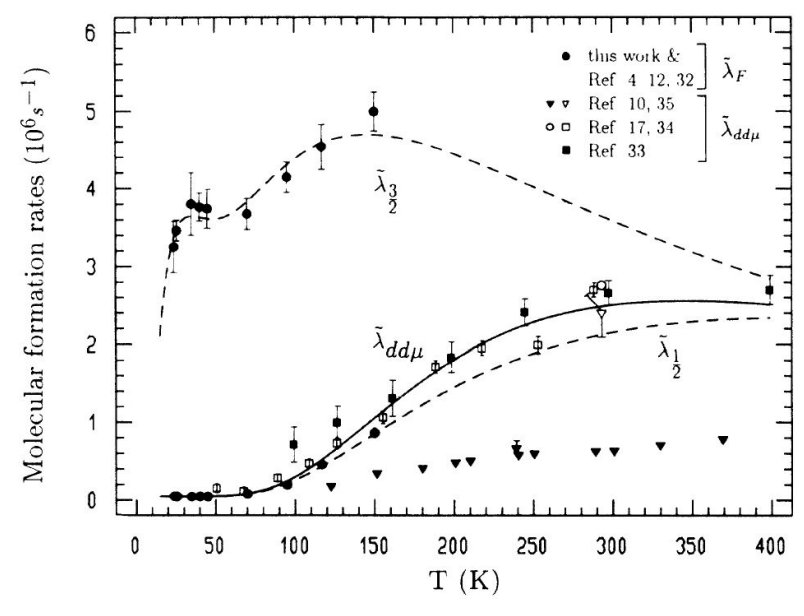
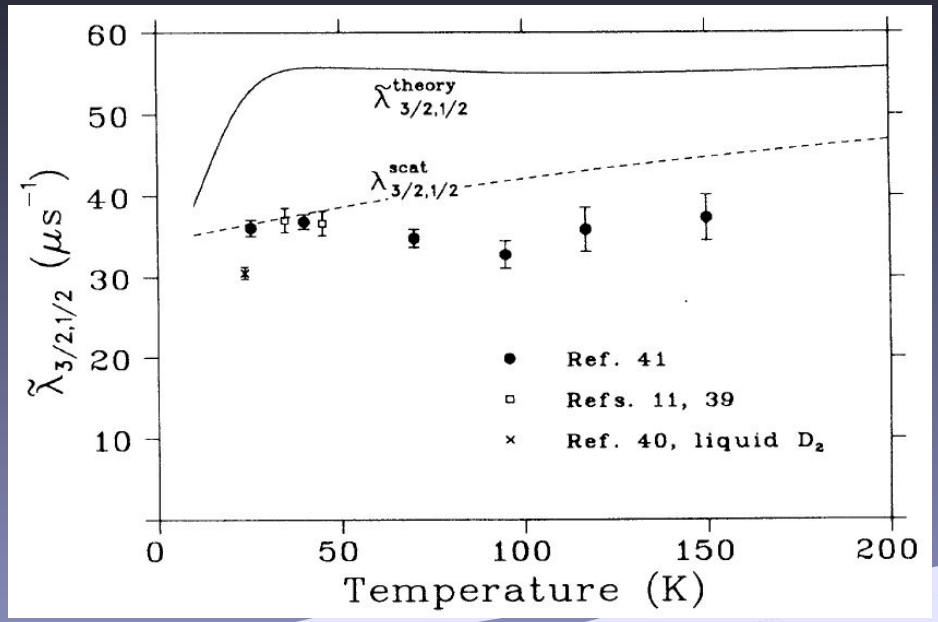






Systematic studies 1979-1988





Rates for LH_2 density

TABLE V. Results of the fit to $\tilde{\lambda}_{1/2}$ and $\tilde{\lambda}_{3/2}$ and theoretical values.

Quantity	Fit	Calculation	Ref.
ε_{11} (meV)	−1966.1(2)	−1966.2[a]	[34]
λ_1 (μs^{-1})	0.044(5)		
λ_2 ($eV^{-1}\mu s^{-1}$)	$\lesssim 1.0$		
$\tilde{\lambda}_f$ ($\alpha=1.0$)	314(33)		
$\tilde{\lambda}_f$ ($\alpha=0.5$) (μs^{-1})	386(51)		
$\tilde{\lambda}_f$ ($\alpha=0.36$)	461(87)		

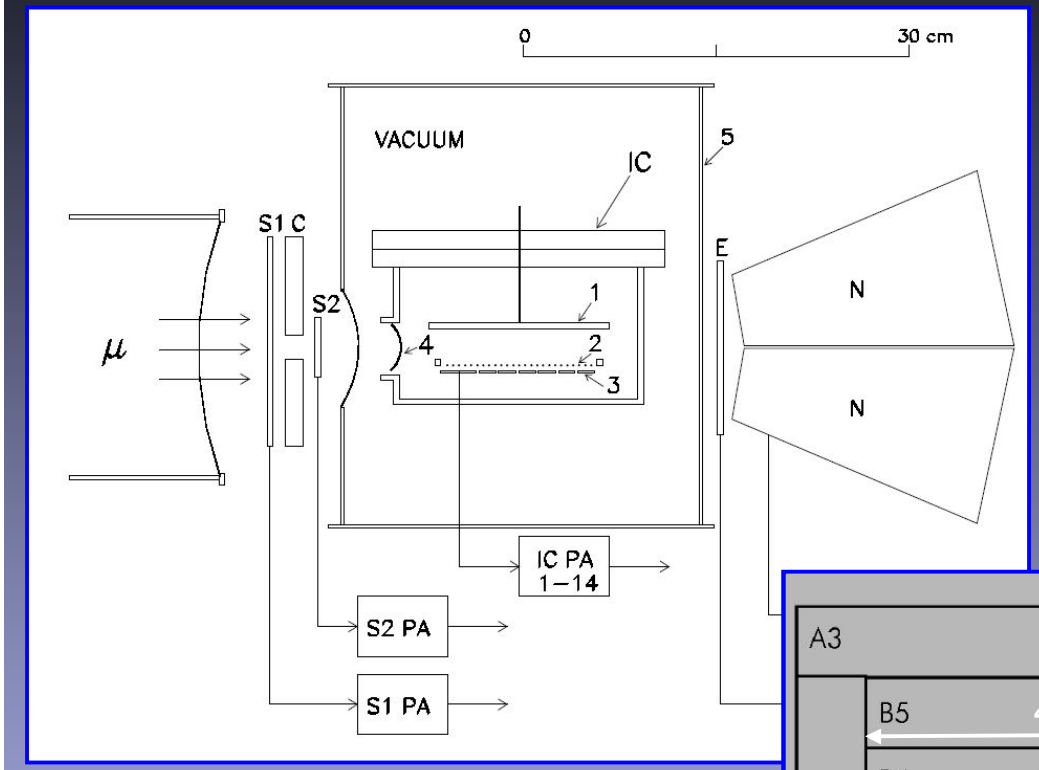
[a]Includes an estimated $dd\mu$ finite-size correction of +(

10^{-7} of muonic Rydberg energy

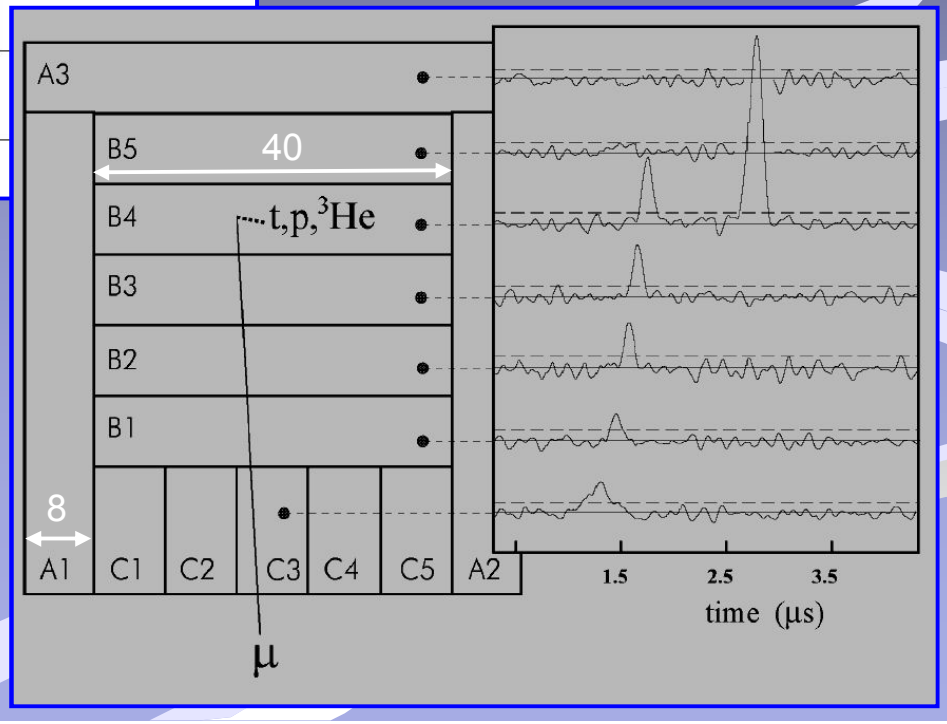
TABLE XIII: Relativistic and other corrections (meV) to the non-relativistic binding energy ε^{nr}_{11} of the (J= 1, ν = 1) level in the ddμ molecule [50].

Vacuum polarization	8.720
Electromagnetic structure of nuclei	-1.675
Relativistic	1.650
Finite size correction	1.46
Nuclear polarization	0
Total shift	**10.16**
Non-relativistic energy ε^{nr}_{11}	-1974.985 [26]
Total energy ε_{11}	**-1964.83**

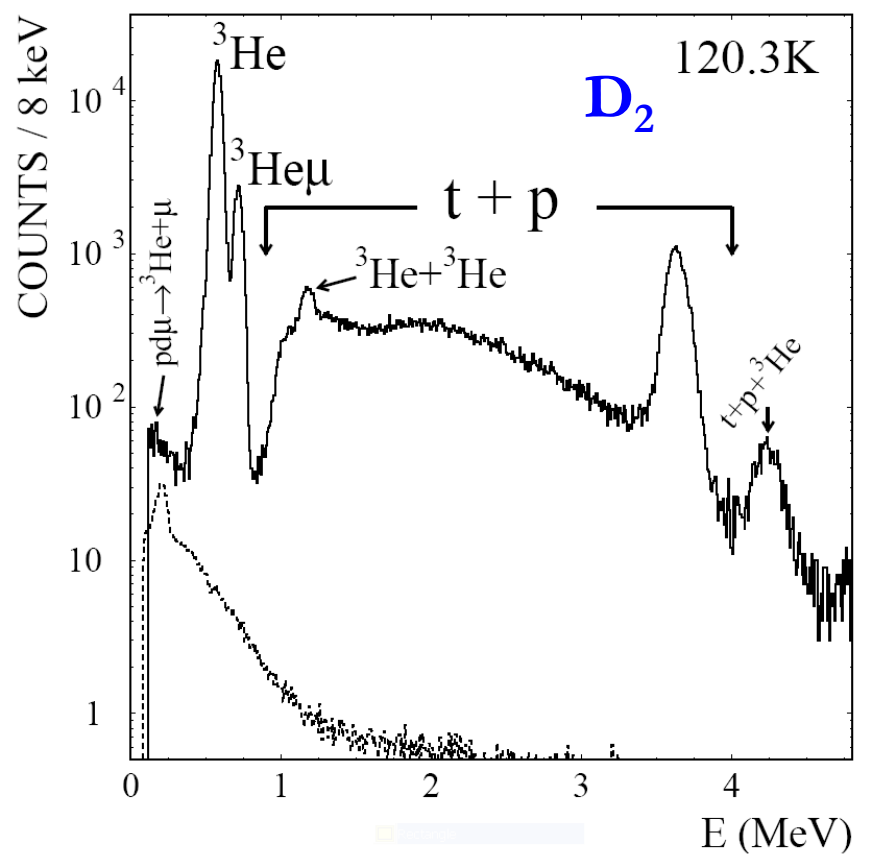
TPC - Ionisation chamber

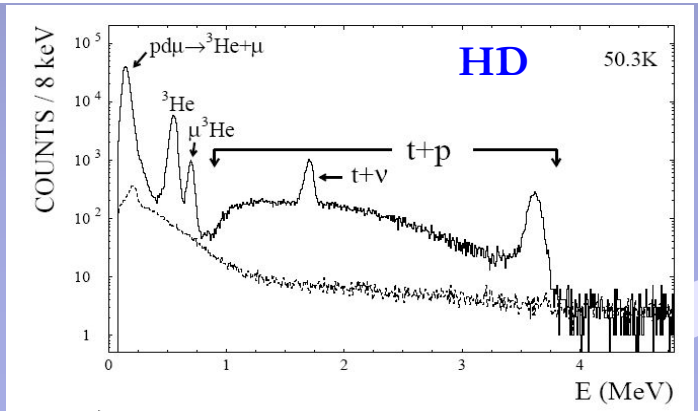


p	45-120 bar	E(kV/cm)
an-grid	1 mm	40
grid-cath	13 mm	25
area	50x52 mm^2	
drift vel.	7 mm/μs	
E_L, E_H	120, 800 keV	



Energy spectra





$dd\mu \rightarrow {}^3He + \mu + n$ (3.27 MeV)

$\rightarrow {}^3H + \mu + p$ (4.03 MeV)

	E (MeV)	E_{obs} (MeV)	R (mm)
^{3}He	0.82	0.6	0.18
^{3}Heμ	0.80	0.75	0.6
t	1.01		1
p	3.02		16

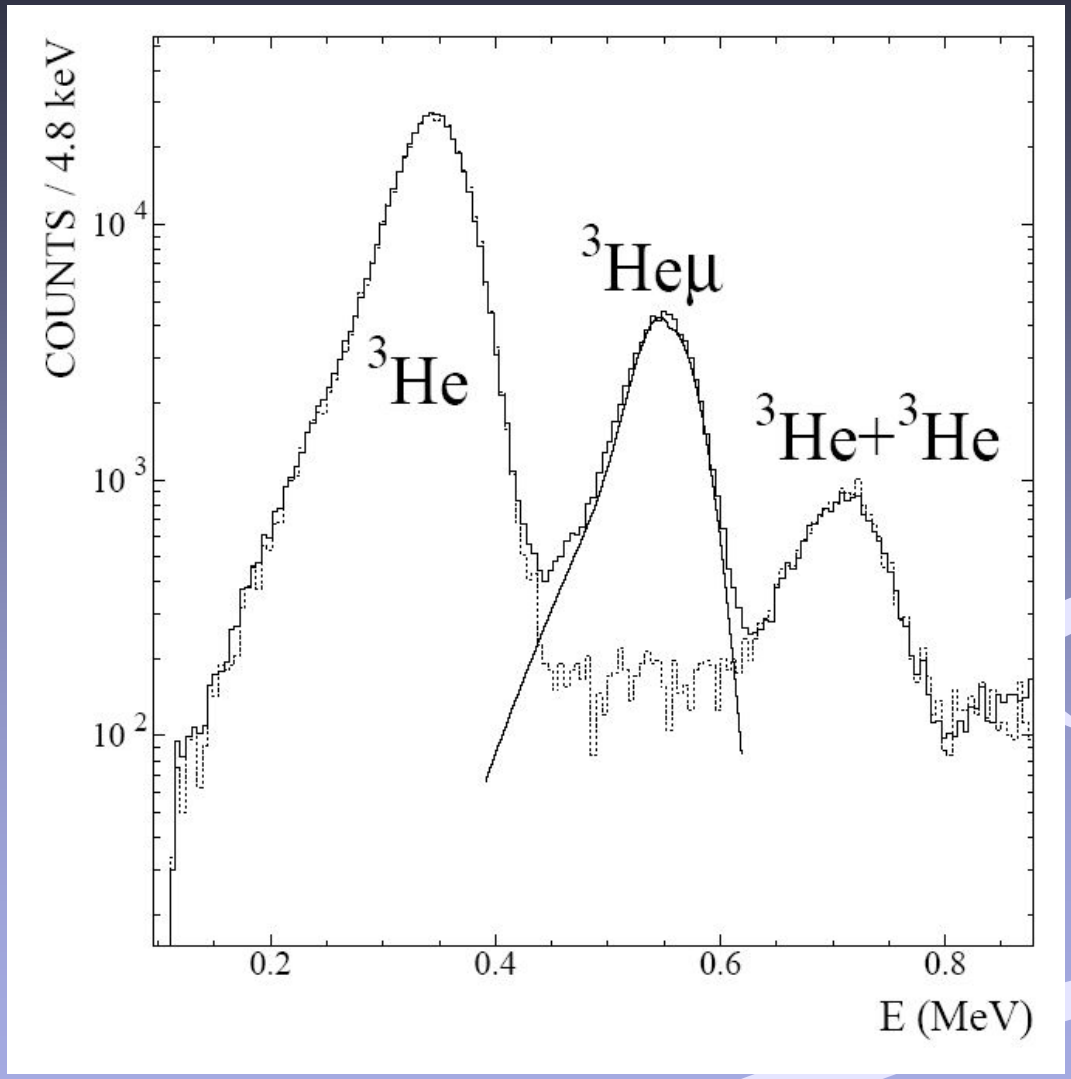
Background

$pd\mu \rightarrow {}^3He$ (0.2 MeV) + μ (5.3 MeV)

$^3He\mu \rightarrow {}^3H$ (1.9 MeV) + ν

$N_Z\mu \rightarrow N_{Z-1} + \nu$

Sticking



"survived muon method"

$dd\mu \rightarrow (^3He\mu)^* + n$ ω^0

$\llcorner\ ^3He + \mu$ R

$\omega = \omega^0 (1-R)$

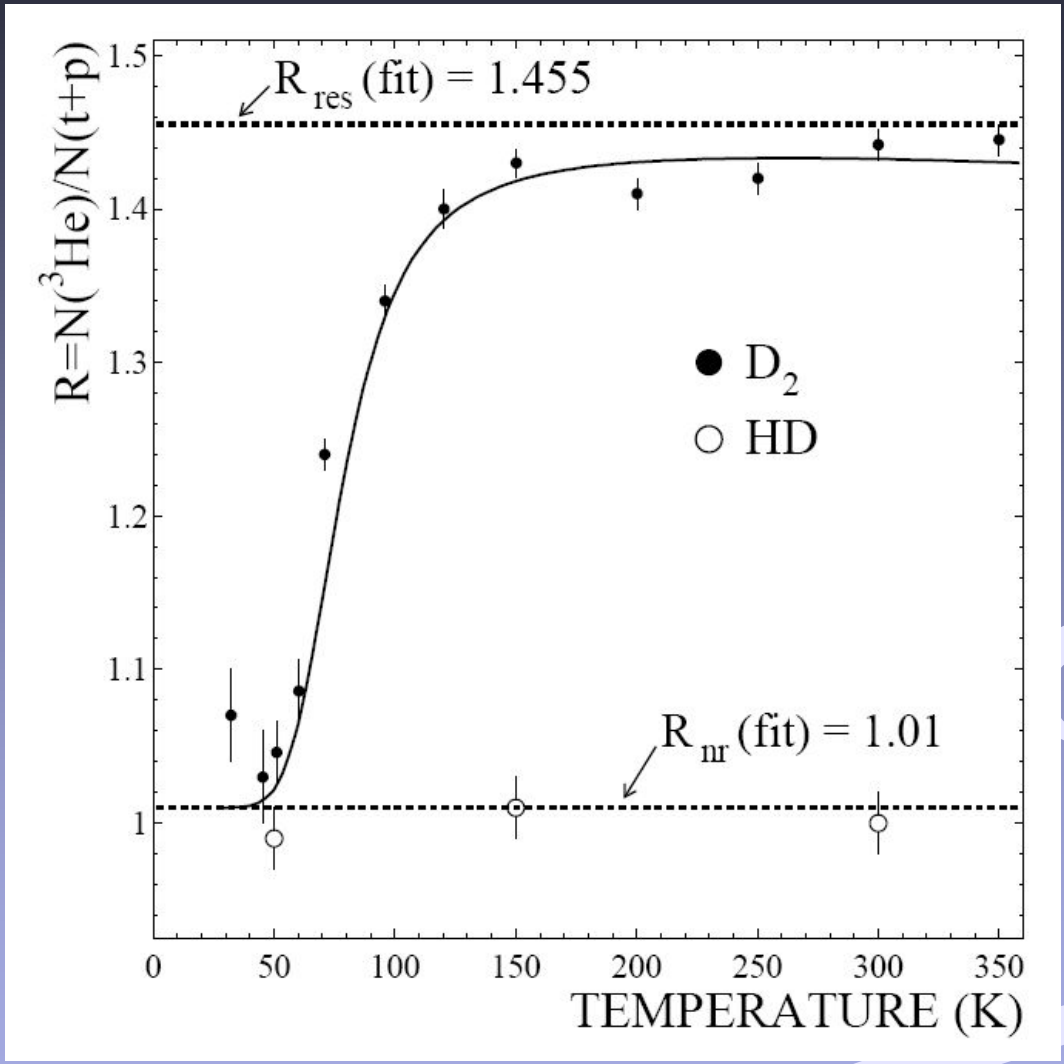
$\omega_{exp} = 0.1224(6)$

$\omega^0_{th} = 0.134\ (3)$

$R = 0.010\ (1)$

$\omega_{th} = 0.120(4)$

Fusion branching ratio



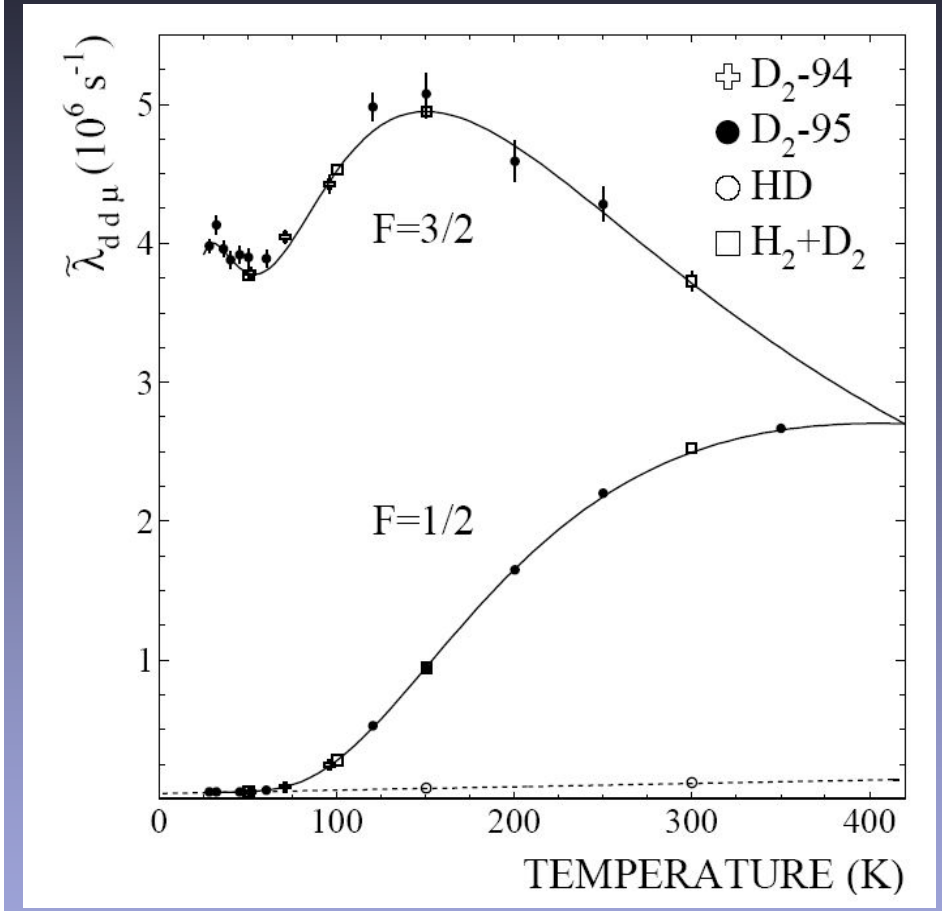
resonant $(dd\mu)_{J=1}$ formation prepares pure P-wave state at "zero" energy

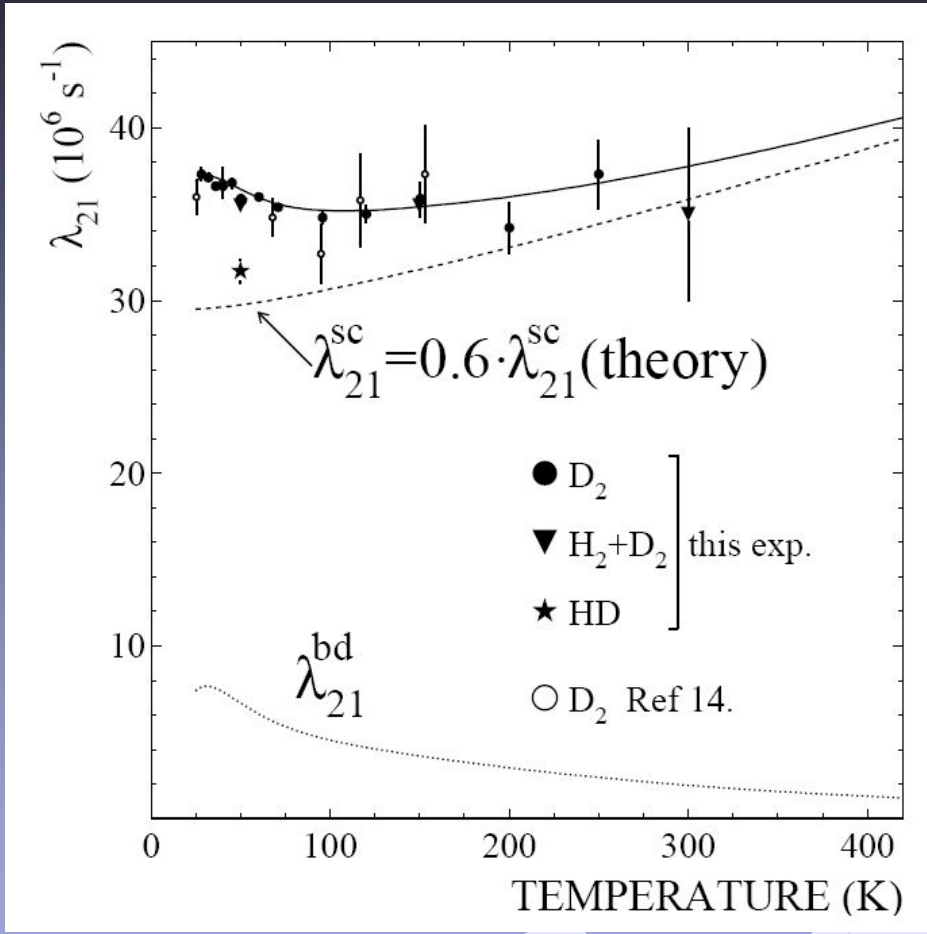
$R = N(^3He)/N(t+p)$

$R_{J=1} = 1.455(11)$

^{4}He structure:
Coulomb isospin breaking amplified by nearby P states of opposite isospin

Hyperfine effects





50-300 K, 1% absolute precision, D_2 and HD data