Determination of μd chemistry kinetic parameters

Mini Collaboration Meeting, 2014

Experimental Goal and Motivation

Measure muon capture rate in deuterium to a precision better than 1.5%

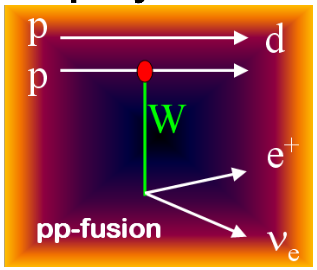
$$\mu^- + d \rightarrow n + n + \nu_\mu$$

Rate Λ_d from μd $(\uparrow\downarrow)$ atom

Impact understanding of fundamental reactions of astrophysical interest, like

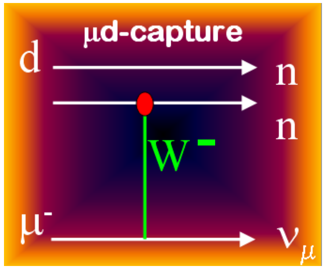
- Solar pp fusion

  $p + p \dashrightarrow d + e^+ + \nu_e$



- Sudbury Neutrino Observatory observed

  $\nu + d$ reactions

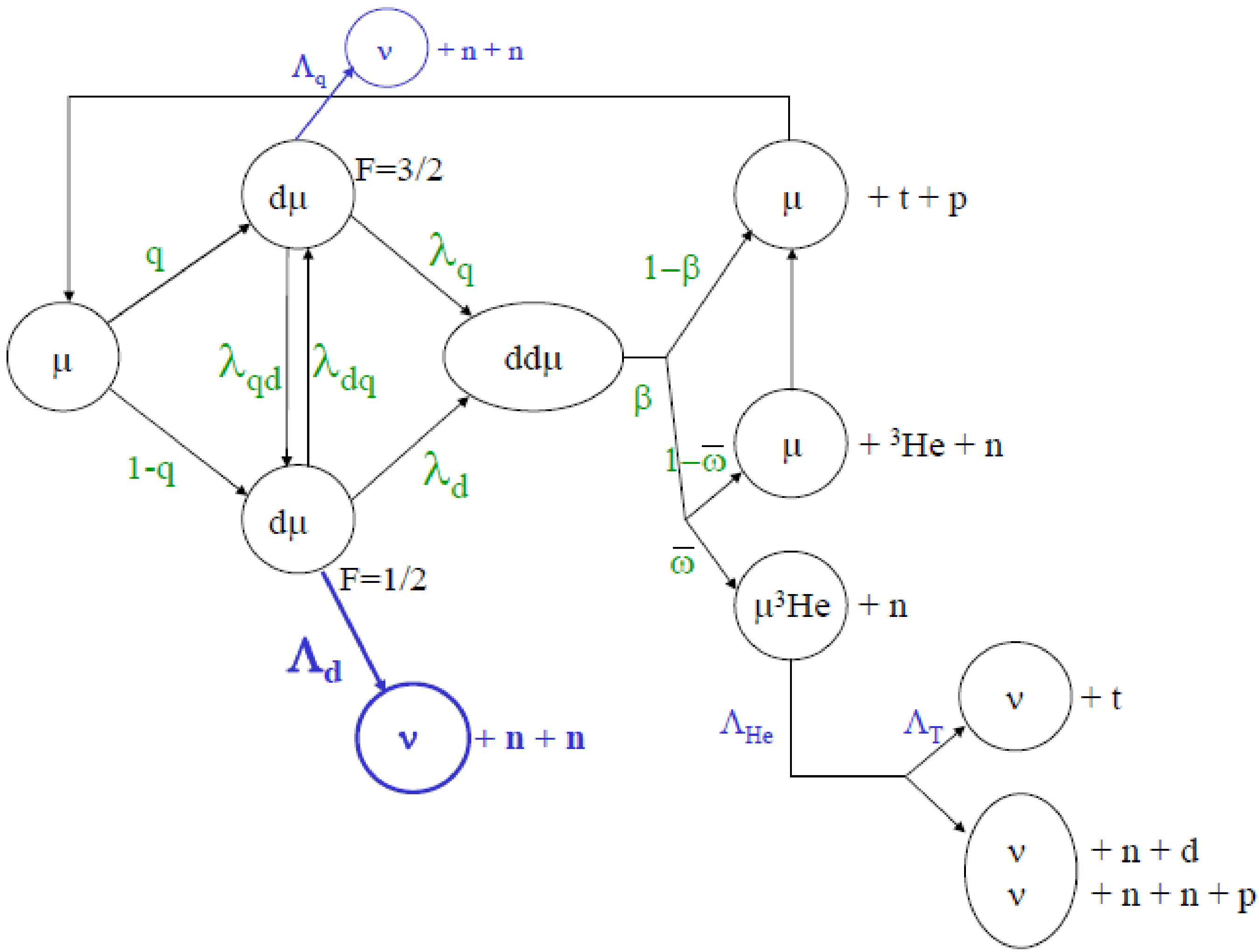


Since they ~ muon capture reaction.

Close relation to neutrino/astrophysics

Recent effective field theory calculations have demonstrated, that **all** these **reactions are related** by one axial two-body current term, parameterized by a single low-energy constant determined by the muon capture rate Λ_d

Muon Chemistry



Experiment Overview

Experimental Setup:

Muons (Z - axis) enter Al vessel (~ 3 mm)– TPC (10 x 10 x 8.2 cm).
X - horizontal and Y - vertical. Target deuterium.

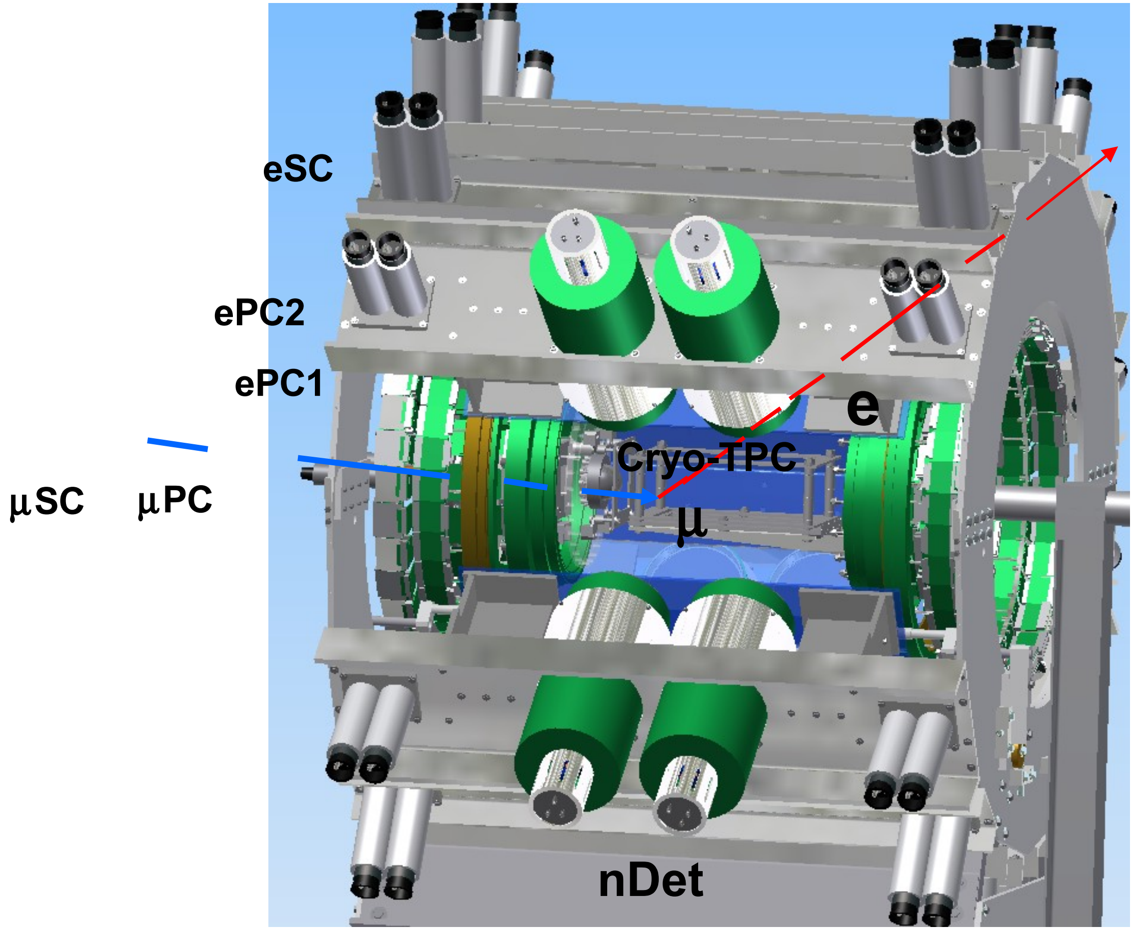
eSC: Electron Scintillator

ePC: Electron Projection Chamber

μPC: Muon Projection Chamber

μSC: Muon Scintillator

nDet: Neutron Detectors



Neutron Analysis

Sources of neutrons:

(i) fusion neutrons from

$d\mu d \rightarrow \mu + {}^3He + n$ (monoenergetic 2.45 MeV)

(ii) capture neutrons the $\mu^- d \rightarrow nn\nu$ (peaked at energies 1.3 MeV – energy up to 53 MeV)

Time dependence of fusion neutrons gives ddμ molecular formation rates from F = 1/2, 3/2 hyperfine states (λ_q and λ_d) and the hyperfine transition rate between the two hyperfine states (λ_{qd})

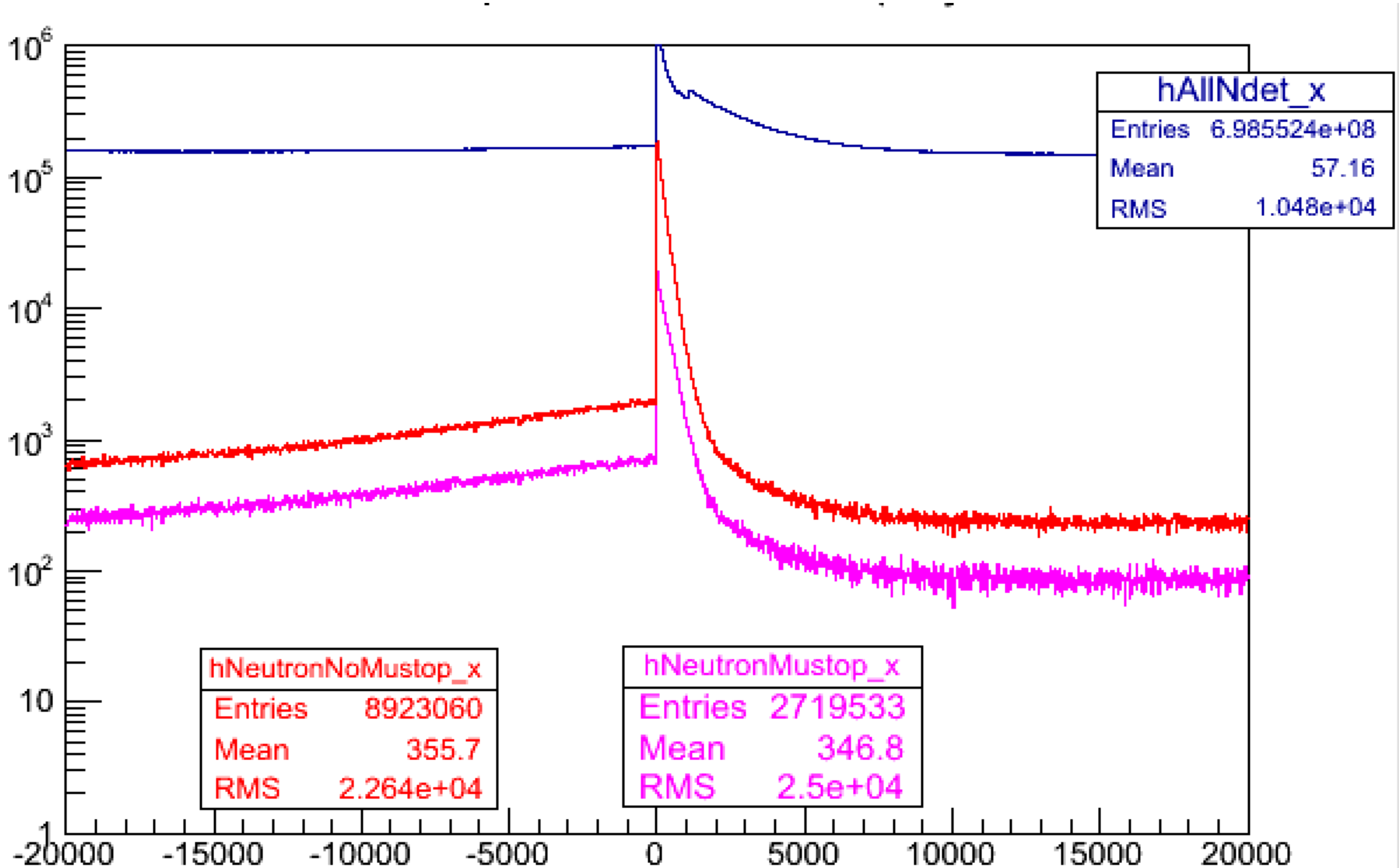
The detection of μ−d capture neutrons helps to find hyperfine transition rate λ_{qd} hyperfine capture ratio λ_q/λ_d.

Neutron Time Spectrum

Pile up protection of muons (one muon enters the TPC in a specific time window $\pm$ 40 μs) - **Blue spectrum** – all pulses seen by the counters (neutrons, gamma rays etc.) - Kinck due to after pulses.

Neutron time spectrum after applying PSD (gamma rays excluded) – **Red Spectrum**

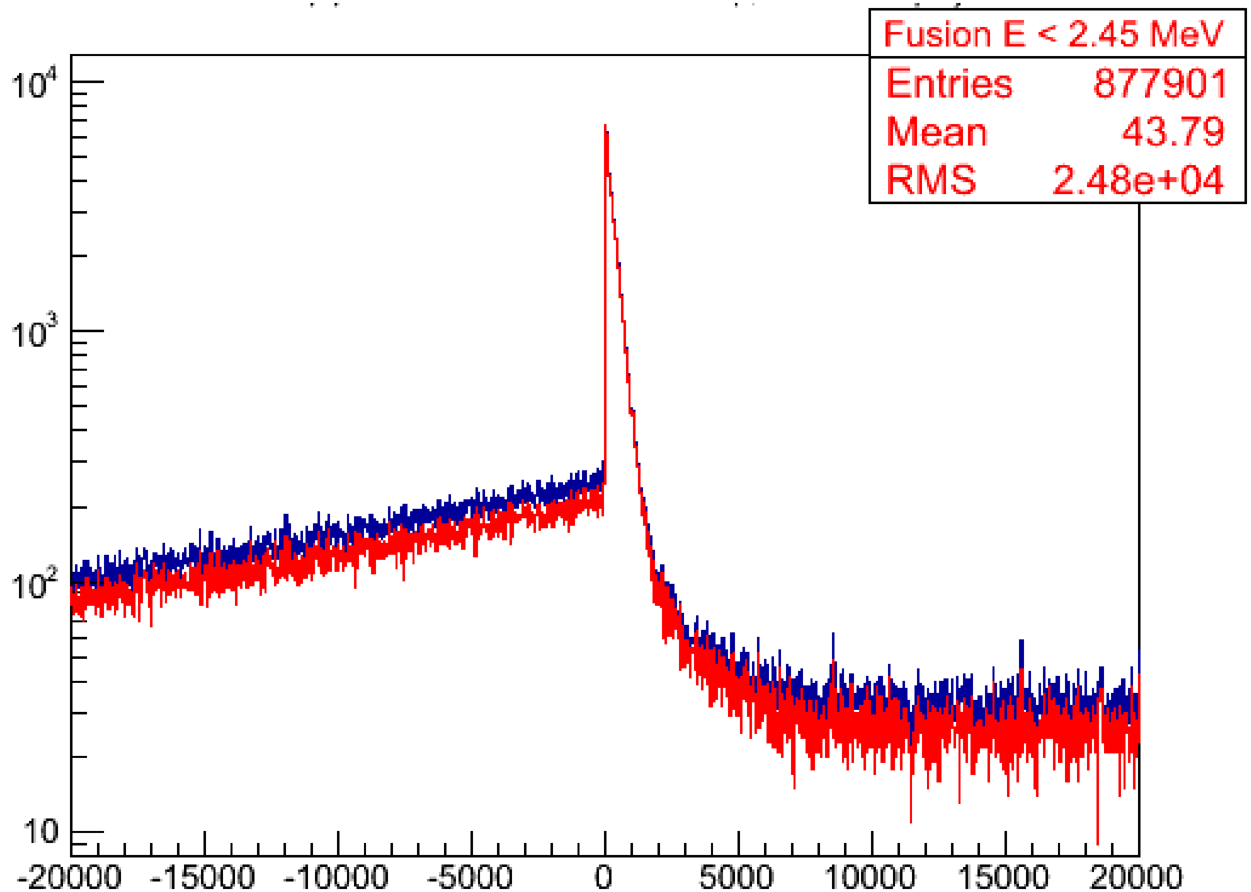
Applied a muon stop condition in the TPC. Includes capture and fusion neutrons – **Magenta Spectrum**. This analysis is for ds_211 (around 1000 midas runs)



$t_n - t_\mu$ (ns)

Fusion Neutron Time Spectrum

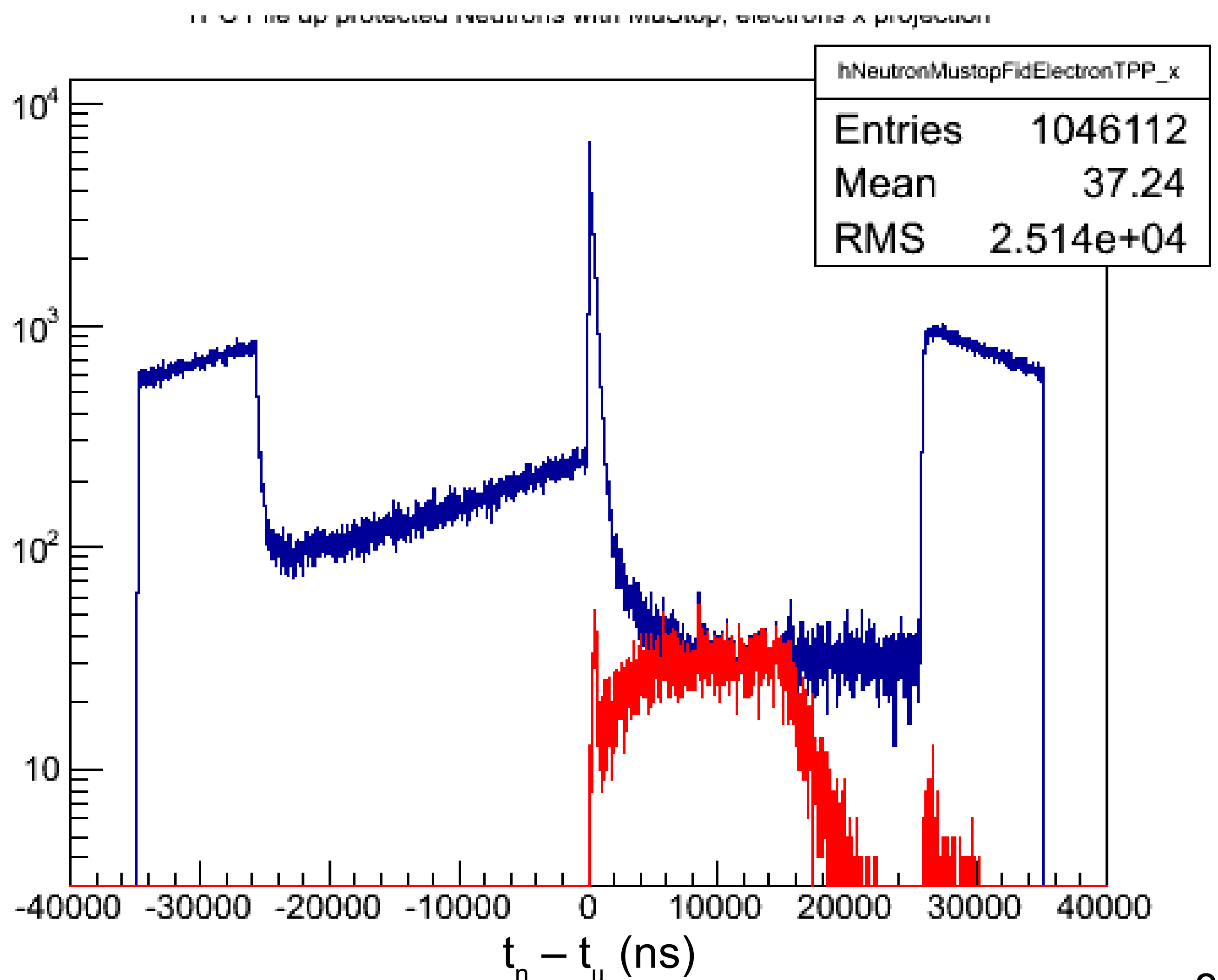
Fusions accompanied by electrons. An electron coincidence with e from fiducial volume of the TPC applied – **Blue Spectrum**
Fusion Neutron are monoenergetic – applied energy cut < 2.45 MeV – **Red spectrum**



$t_n - t_\mu$ (ns)

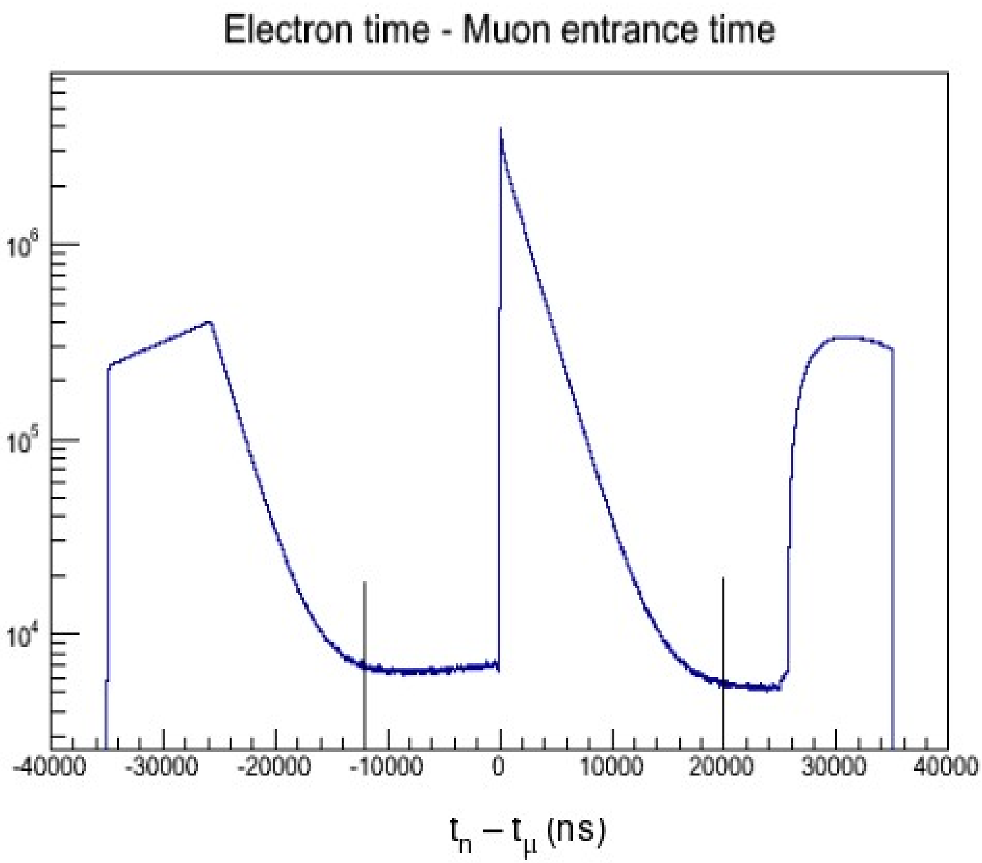
Background Spectrum

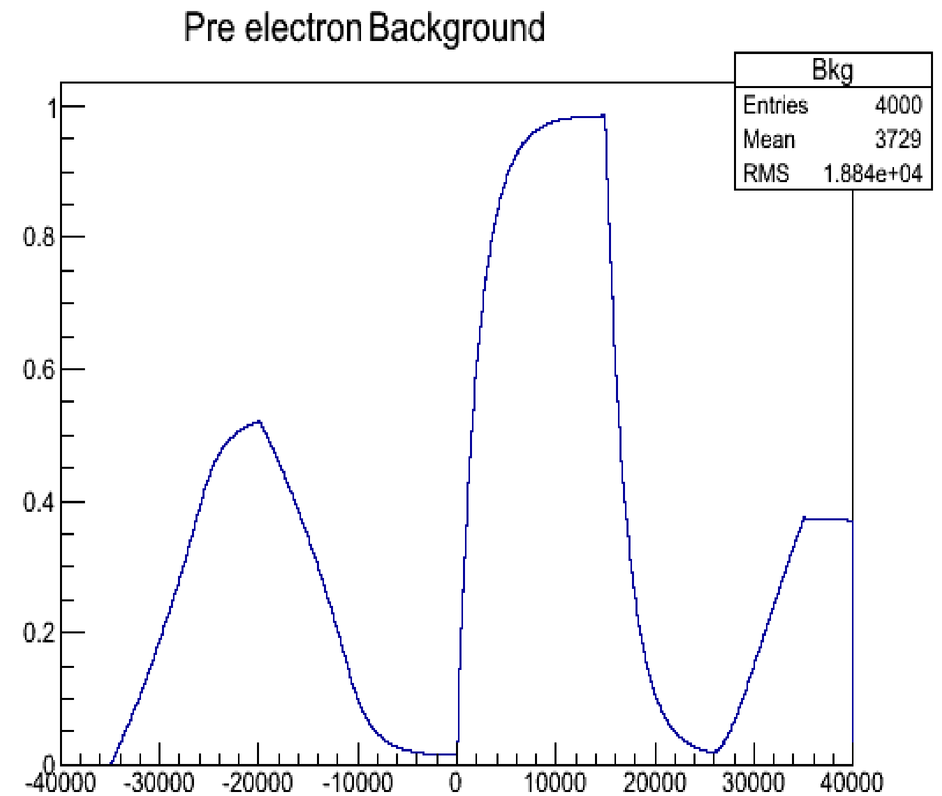
Background – from pre electron condition – electrons before the neutrons are generated   in a window of -100 to -15000 ns time of electron time wrt to neutron time **Red spectrum.**



Background Spectrum

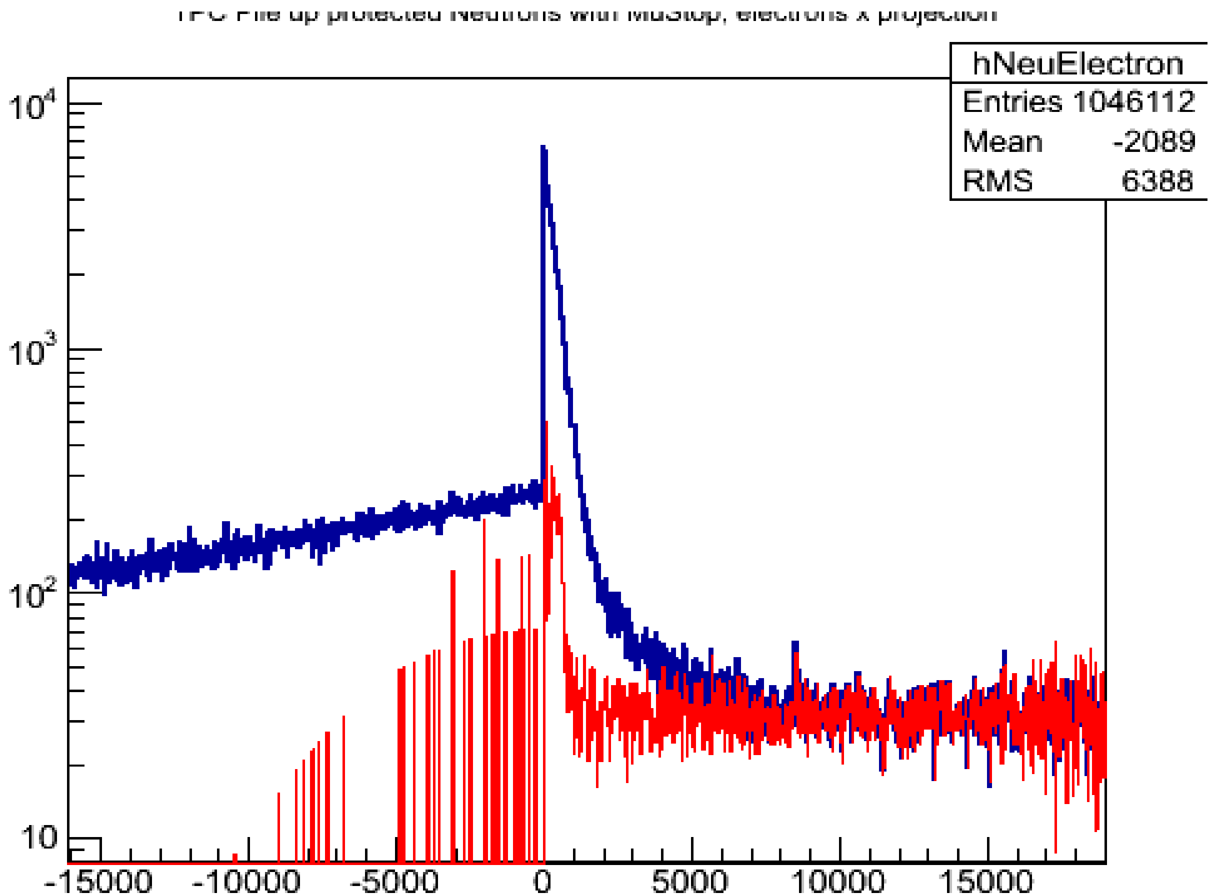
Electron association window is shown in the left panel. Probability for electrons to leak in the background window is found by shifting the pre electron window over every bin of the neutron spectrum divided by the area shown in the left (which is the sample space). Output of this in the right figure is the efficiency function.





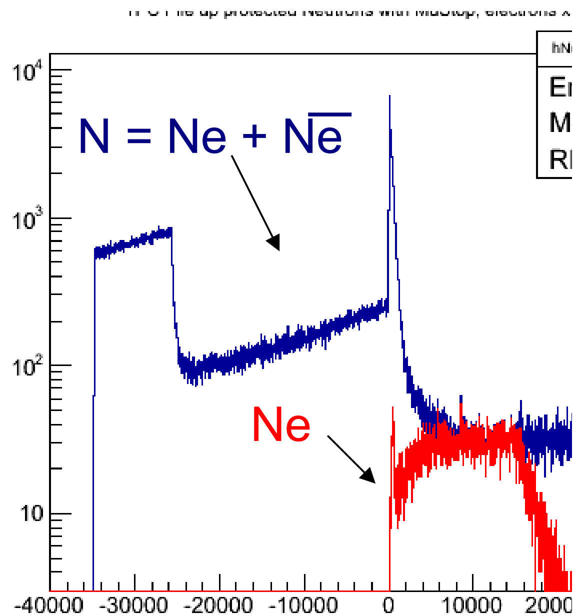
Background Spectrum

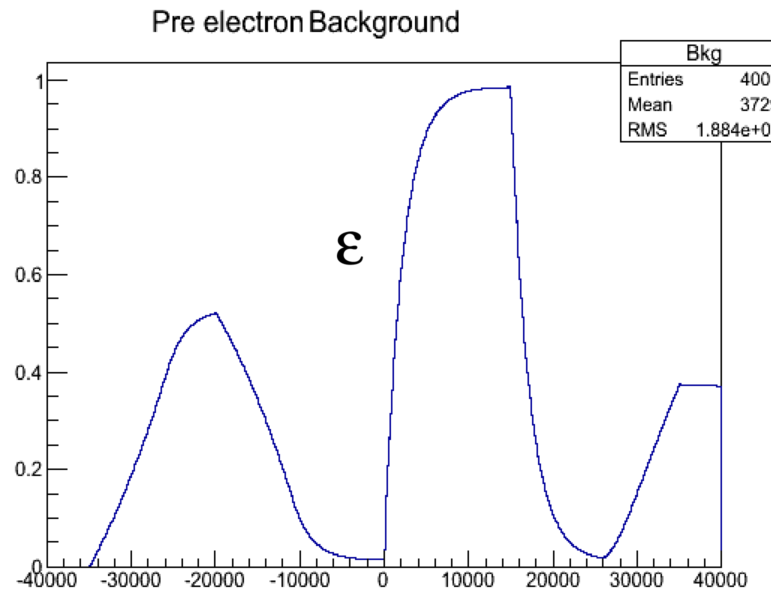
Efficiency function was divided by the pre electron spectrum - **red spectrum**
Overlaid on original fusion spectrum – **blue**
Subtracting the spectra shown below gives final background subtracted fusion spectrum



Error Propagation – Lifetime fit

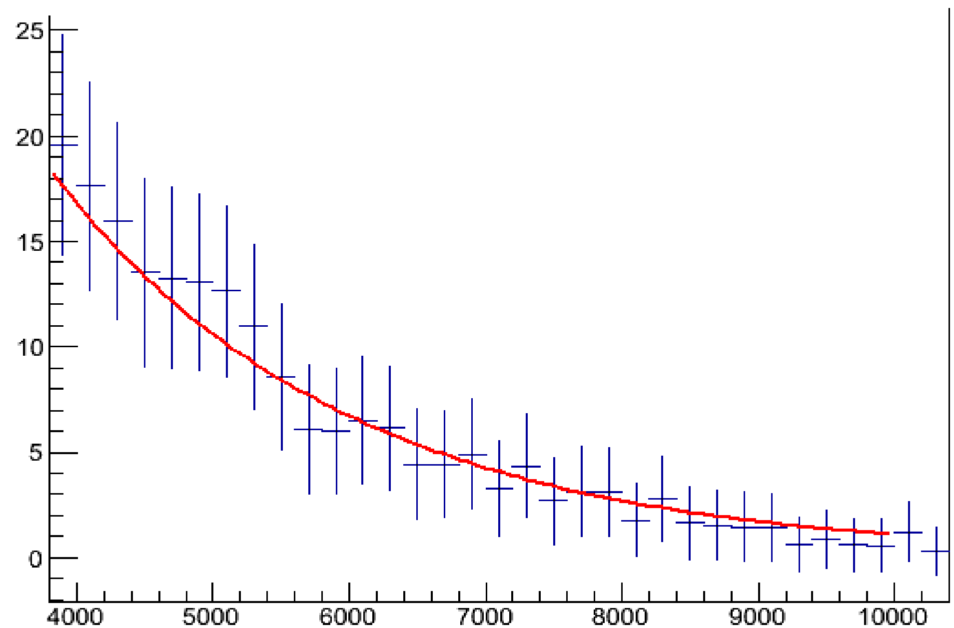
Blue spectrum = pre electron and no pre electron – used two uncorrelated components
Red – only pre electron
Right spectrum efficiency ε





Final fusion spectrum

$Nf = Ne + N\overline{e} - Ne/\varepsilon$



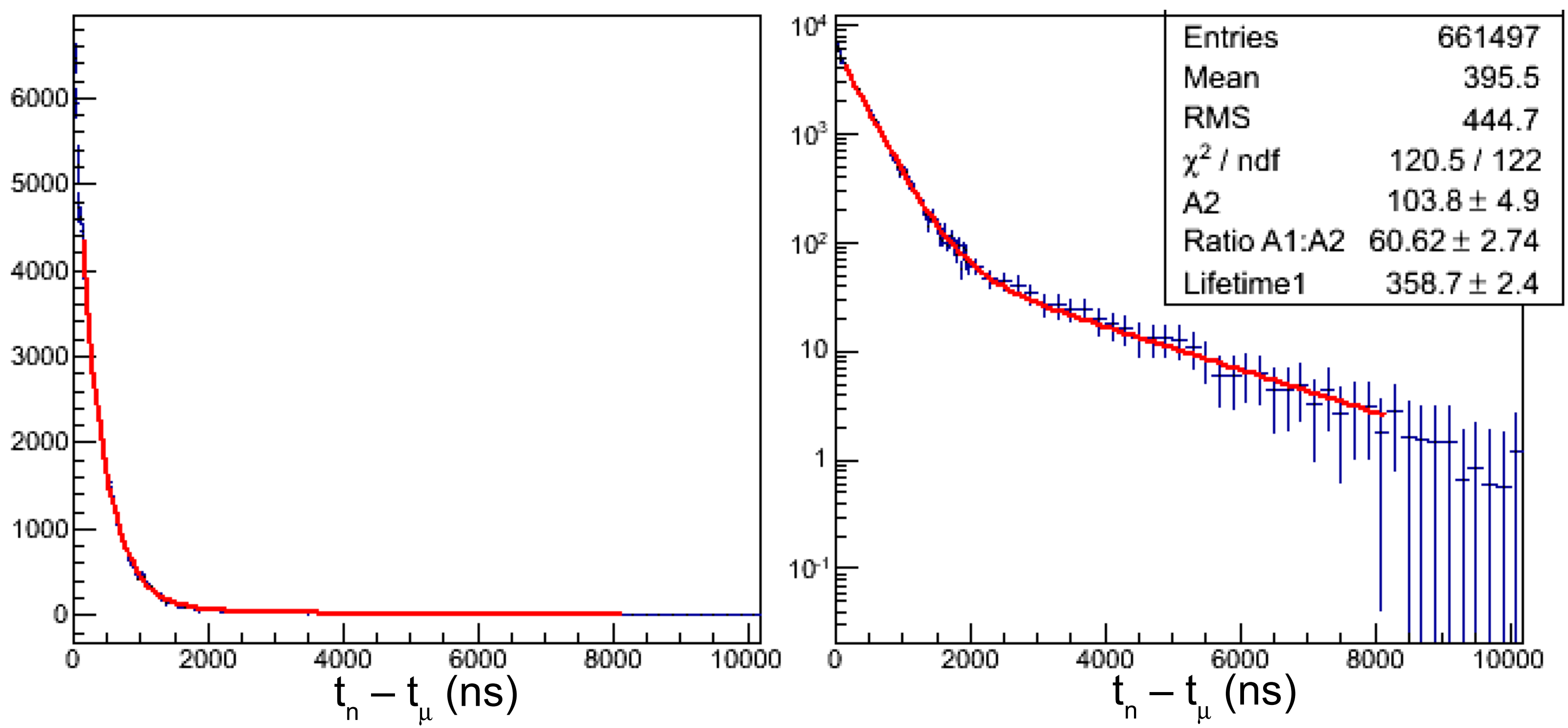
Errors were evaluated based on the above equation after rebinning each spectra 10 from ~ 2000 ns. Results for a small range shown in the right plot. Previous slide has full spectrum errors (in log scale)

Fusion Spectrum Lifetime Fit

Background subtracted. Fit function - two lifetime fit function on a flat background = 0. Slow lifetime component is fixed it ~ 2197 ns. (muon lifetime). Reduced χ^2 of 0.987. Spectrum rebinned by a factor of 10 beyond 1800 ns

Fit Parameters used:

- A1:A2 = Amplitude ratio (amplitude – initial population)
- Prompt Lifetime
- A1 – Initial population of quartet state



Analytical Solutions – Lifetime fit

The amplitude ratio used in our fit is derived by solving analytically the coupled differential equations obtained from the muon chemistry.

Two lifetime fit of fusion is taken to be,

$$n(t) = A_1 e^{-\lambda_1 t} + A_2 e^{-\lambda_2 t}$$

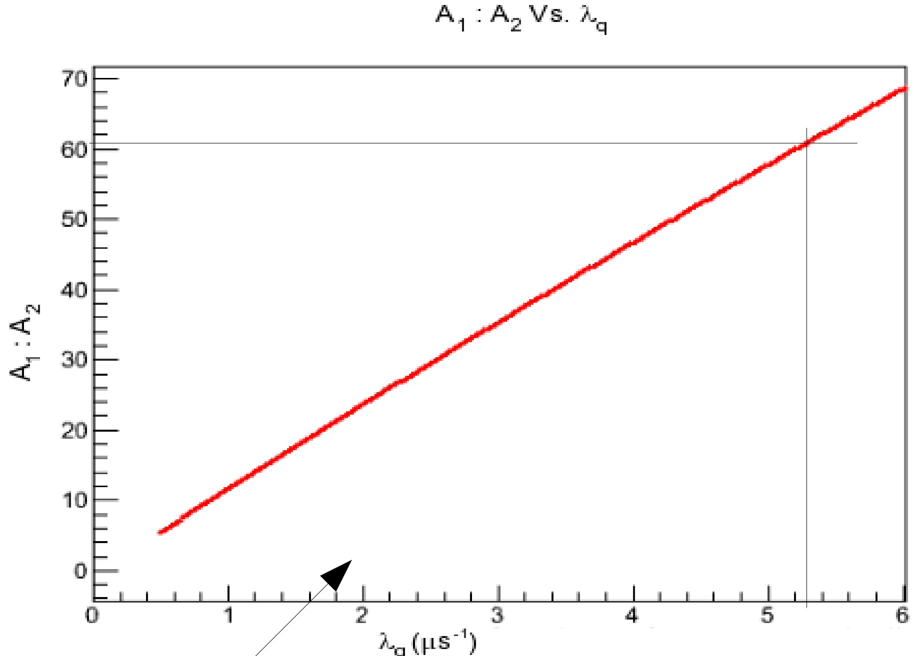
Prompt lifetime, $$\lambda_1 \approx \frac{-1}{3}\left(\phi\left((1+2s)\lambda_q + 3\lambda_{qd}\right) + 3\lambda_\mu\right)$$

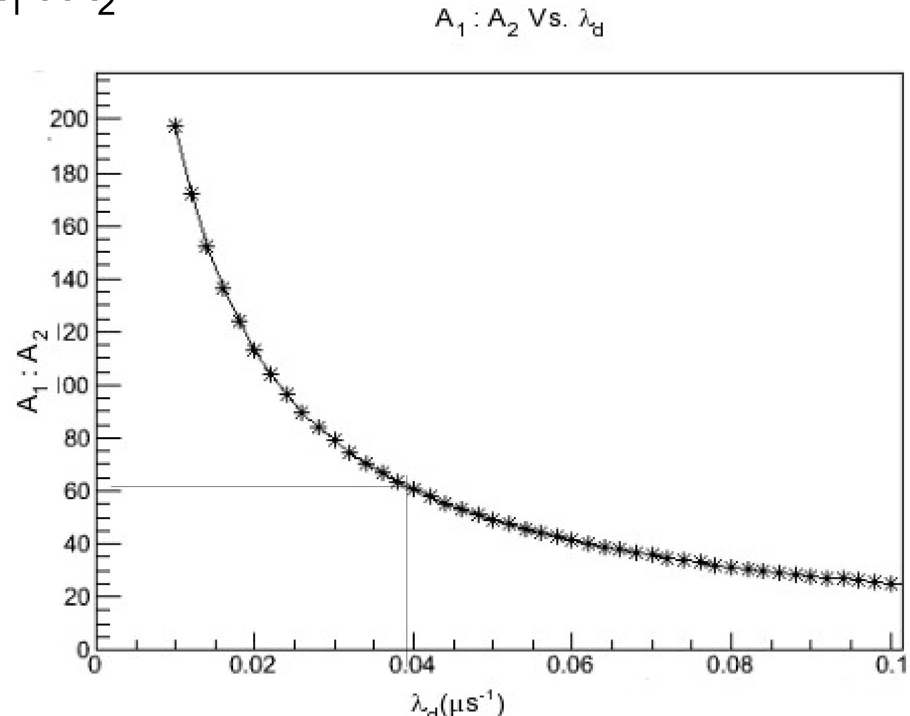
Long lifetime, $$\lambda_2 \approx \frac{-1}{3}\left(\phi\left((1+2s)\lambda_q\right) + 3\lambda_\mu\right)$$

Amplitude Ratio, $$\frac{A_1}{A_2} = \frac{(\lambda_d X_1 + \lambda_q)(2X_2 - 1)}{(\lambda_d X_2 + \lambda_q)(1 - 2X_1)}$$

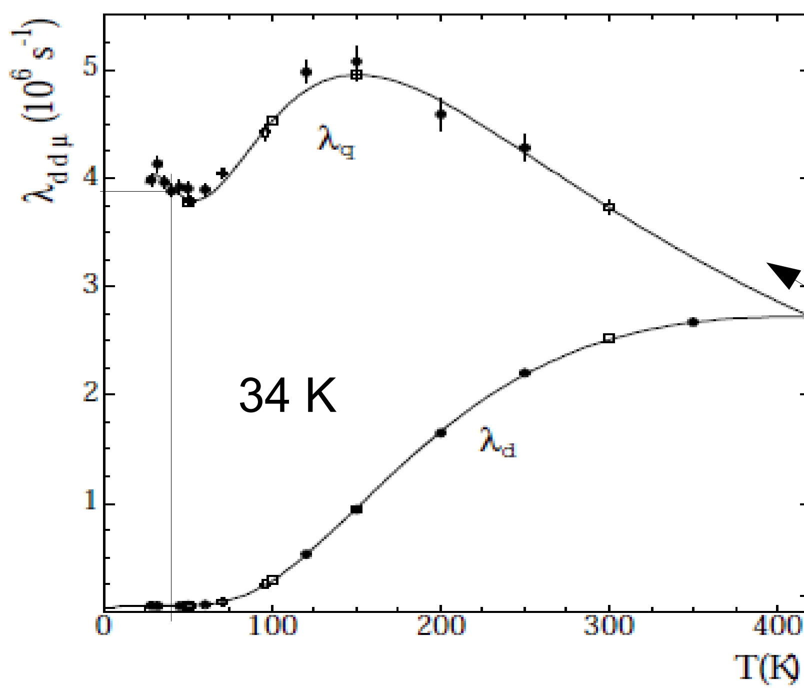
Analytical Solutions – Lifetime fit

Effect of changing various parameters on $A_1 : A_2$





From data fit
A_1:A_2 = 60.62
λ_d ~ 0.039 μs^{-1}
λ_q ~ 5.28 μs^{-1}



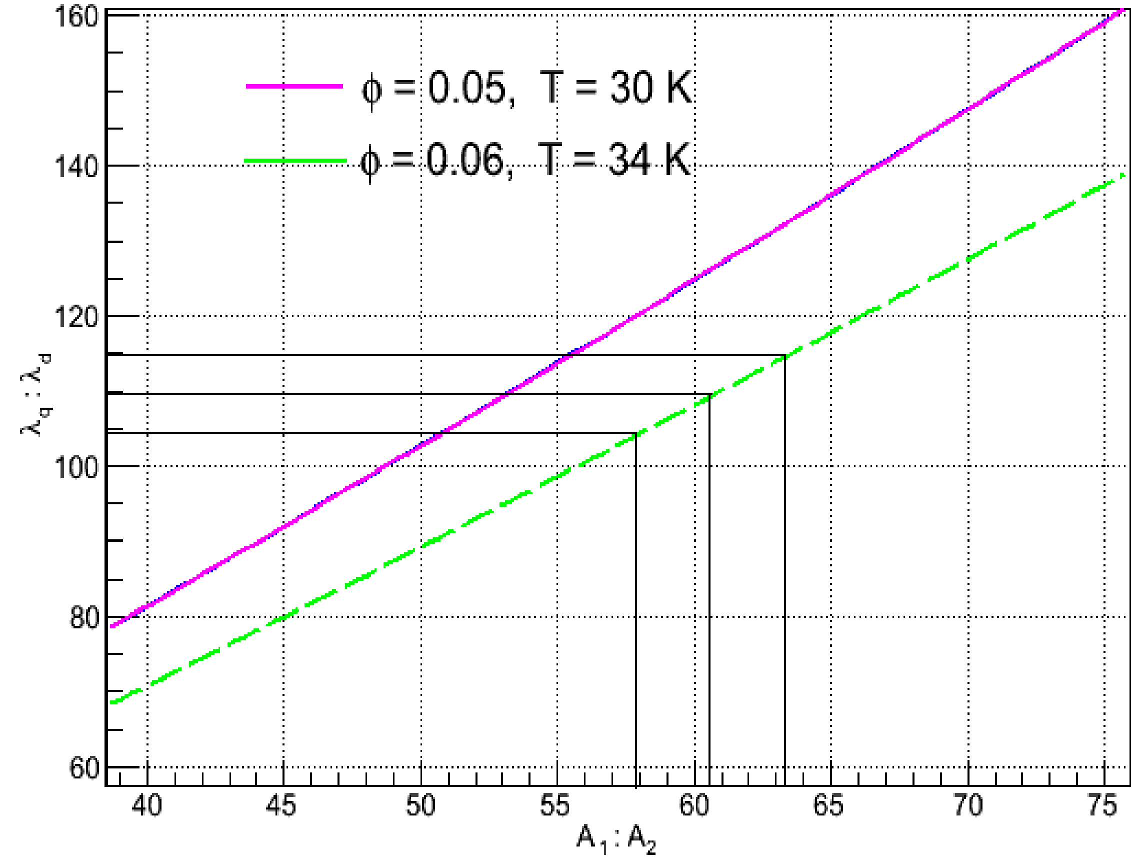
Prop Values at 30 K
λ_d ~ 0.053 μs^{-1}
λ_q ~ 3.98 μs^{-1}

Values at 34 K (from plot on left)
λ_d ~ 0.053 μs^{-1}
λ_q ~ 3.88 μs^{-1}

Preliminary Results

The prompt lifetime extracted the transition rate of muonic deuterium from quartet to double state (equation solved analytically). Temp 34 K and density 6% LH2

$\lambda_{qd} = 45.26 \pm 0.203\ \mu s^{-1}$



The dμd formation rate from quartet state to double state found using the plot (obtained from analytical solutions).

$\lambda_q / \lambda_d = 109.59 \pm 5.14$

Previous μCF experiment result temp 32.2 K and density 5.14% LH2 :

$\lambda_{qd} = 37.1(3)\ \mu s^{-1}$

$\lambda_q / \lambda_d = 80.98(4)$

$$\frac{A_1}{A_2} = \frac{(\lambda_d X_1 + \lambda_q)(2X_2 - 1)}{(\lambda_d X_2 + \lambda_q)(1 - 2X_1)}$$

Systematic Errors - Sources

In a previous analysis I completed a set of systematic error analysis – to near completion for this method. The fit results were extremely stable, and sources of these errors were found to be due to:

✧An imperfect pile up protection – accidental external muons in coincidence with the muon in consideration
✧Fiducial volume and other backgrounds in the muon stop definition
✧Misidentified muon stops like a fusion causing confusion
✧Misidentified electrons due to imperfect pile up protection and accidental electrons
✧Electrons not emanating from the fiducial volume of the TPC to eSC, but rather in opposite direction
✧Background spectrum being sensitive to electron Bremsstrahlung, afterpulses in neutron detectors, misidentified gamma rays etc.

Meticulous cuts were made to minimize these effects and all cuts corresponding to these effects were varied to investigate the effects

Back up Slides

Table of Systematic Errors

Shows stable fit results, except the highlighted values of A_2

	Cuts	λ_1	A_2	$A_1 : A_2$	χ^2
Pre Electron Window	-10000 to 100 ns	358.2±2.4	103.4±4.9	61.05±2.77	0.97
	-20000 to 100 ns	358.2±2.3	104.7±4.8	60.49±2.69	1.0
	Variable	358.2±2.1	106.6 ±4.8	60.55 ±2.61	1.17
Energy Cut	E<2.45 MeV	359±2.3	102.2±4.8	61.51±2.78	0.99
	E<1.5 MeV	361±2.6	72.31±4.8	64.82±3.48	0.95
	E<5 MeV	358.6±2.4	103.6±4.9	60.74±2.74	0.99
Neutron threshold energy	Increased	358.6±2.4	98.13±4.73	60.07±2.78	1.03
	Decreased	358.6±2.4	104.4±4.9	60.43±2.72	0.99
Neutron cutoff energy	Increased	358.6±2.4	104.3±4.9	60.45±2.72	0.99
	Decreased	358.6±2.4	104.3±4.9	60.45±2.72	0.99
Fiducial volume	Increased	359.2±2.0	158.6±6.1	61.27±2.25	0.97
	Decreased	349.6±6.5	13.07±1.62	57.18±6.81	0.62
Senergy	>600	358.8±2.4	103.6±4.9	60.67±2.75	0.99
	>900	358.8±2.4	103.2±4.9	60.8±2.8	0.98
Stop in Z - pad	≥ 4	357.7±2.5	91.2±4.5	60.31±2.88	1.05
	$\geq 3(default)$	358.7±2.4	103.8±4.9	60.62±2.74	0.99