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PROGRESS REPORT ON MUON CATALYZED FUSION STUDIES IN $H_2 + D_2$ AND HD GASEOUS TARGETS

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Last year at the Gatchina Conference we reported (1) results on $dd\mu$ and $pd\mu$ fusion product yields from gaseous targets of H_2 + D_2 and HD. These results were so different from theoretical expectations in the case of fusion neutrons from HD and fusion gamma rays from both HD and H_2 + D_2, that we felt it prudent to remeasure these processes in a new experimental arrangement.

In December, 1987 we ran at TRIUMF. We will report on that portion of the data which we have analyzed since our latest run, that is, on gamma ray yields from the muonic molecule $pd\mu$. Table 1 compares the experimental conditions for the April 1985 data (reported at Gatchina) and our December 1987 run.

TABLE 1

COMPARISON OF EXPERIMENTAL CONDITIONS FOR TWO SETS OF MEASUREMENTS.

50 ATM GAS TARGETS (20° C)ρ = 0.058 LH_2 DENSITY

	April 1985	December 1987
Targets		
	$50\%H_2 + 50\%D_2$	$83\%H_2 + 17\%D_2$
	$25\%H_2 + 50\%HD + 25\%D_2$	$56\%H_2 + 38\%HD + 6\%D_2$
	$88\%H_2D + G\%H_2 + 6\%D_2$	$48\%H_2 + 52\%HD + 6\%D_2$
Channel		
	M20A	M13
	8KHz $\mu-$	56KHz $\pi-$
	0.5KHz e-	120KHz e- 8 KHz μ^-
HD Source		
	homemade	purchased

Other differences: A new target was constructed for December, 1987. Because of the large π^-/e^- contamination in M13 a different trigger was used. This entailed different logic and hence both the data acquisition and data analysis computer codes were rewritten from the earlier (April 1985) runs.

Our original interest was simply to measure $\lambda_{dd\mu-p}$ and compare it to $\lambda_{dd\mu-d}$. We intended to use the fusion gamma ray-from

$p + d \rightarrow {}^3He + \gamma$ as a monitor. Since the $pd\mu$ molecule has no loosley bound states it is believed to be formed via a non-resonant mechanism.[2] which is calculated to have a negligible temperature dependence over our range of temperatures. Moreover, since the formation of the $pd\mu$ molecule entails the release of approximately 90 eV of energy we expected molecular structure to be insignificant. That is

$$d\mu + H_2 \rightarrow pd\mu + X \tag{1}$$

and

$$d\mu + HD \rightarrow pd\mu + X \tag{2}$$

should proceed at the same rates. We expected no difference in fusion gamma ray yields (#gamma rays/stopped muon) between cases (1) and (2).

Contrary to these expectations the (H_2+D_2) target gave twice as many gamma rays as the HD target and a temperature dependence was noted.[1] These features of the earlier experiment are corroborated by our recent measurement.

A sample gamma ray spectrum is shown in Fig.1. From such spectra the ratio of fusion gamma rays to decay electrons can be extracted. The yields are shown in figure 2. Very much the same conclusions can be drawn here.

(i) $H_2 + D_2$ gives a larger yield of fusion gammas than $H_2 + HD$.

(ii) The fusion yield from the equilibrated mix seems to be smaller than from the original mix.

Notice that figure 2 gives the yield in arbitrary units. The absolute yield will be discussed shortly.

Let us consider now the conventional picture from ref. 3 of $pd\mu$ formation and subsequent fusion. This will help us contrast more sharply the difference between theory and experiment. One notices that the formation of the J = 2 hyperfine state of $pd\mu$ robs fusion gamma rays. Fusion occurs only in the remaining three states J = 1, 1', and 0.

The $(d\mu)_{J=1/2}$ state populates the $(pd\mu)_{J=1,0}$ states and $(d\mu)_{J=3/2}$ atom populates the $(pd\mu)_{J=1,2}$ states. The enhancement of the J = 1, 1', 0, $pd\mu$ states, and subsequent enhancement of the gamma ray yield, by the transition $(d\mu)_{3/2} \xrightarrow{\phi C_d \lambda_d} (d\mu)_{1/2}$ is called the Wolfenstein-Gershtein effect.

One notices that depending on the population of these hyperfine $(pd\mu)_J$ states the gamma ray yield can vary widely. Using the population as depicted in ref. 3 and an effective value of $\lambda_d = 42 \, x \, 10^6/s$ [5] (i.e. we will neglect the $(d\mu)_{1/2} \rightarrow (d\mu)_{3/2}$ *transition*) we can calculate the expected gamma ray yield ratios. These are tabulated in table 2, along with the measured values.

Table 2

Expected and Measured Yield Ratios of Fusion Gamma Rays from $(pd\mu)) \rightarrow {}^3He\,\mu+\gamma$,

Experiment		Expected	Measured (overall temperatures)
4/1/85	$\frac{Y_\gamma(.5H_2+.5D_2)}{Y_\gamma(HD)}$	1.0	$2.0 \rightarrow 2.2$
12/87	$\frac{Y\gamma(C_d=.17, H_2+D_2)}{Y\gamma(C_d=0.3, H_2+HD)}$	0.9	1.70 ± 0.26

An investigation shows several points where the difference between HD and H_2+D_2 might arise.

(i) Suppose we want to retain $\lambda_{pd\mu-d} = \lambda_{pd\mu-p}$. Then the distribution of $pd\mu$ hyperfine states is a possible parameter to play with. If λ_d depended on the D_2 concentration and not the atomic concentration, i.e., the process for atomic hyperfine transitions is

$$(d\mu)_{3/2} + D_2 \rightarrow (d\mu)_{1/2} + X$$

Then the largest ratio we could expect is

$$\frac{Y_\gamma\,(H_2 + .17D_2, \lambda_d \rightarrow \infty)}{Y_\gamma\,(H_2 + .52HD\,, \lambda_d = 0)} = 1.86$$

However, this is not realistic since λ_d has a known value.

(ii) Keep $\lambda_d(D_2) = 4.2\ x\ 10^6\ s^{-1}$, $\lambda_d(HD) = 0$ then at 50 atm, $(\phi = 0.058\phi_o)$ we get Table 3.

However, this possibility does not seem very strong. At $300°K$ the effective rate for $(d\mu)_{3/12} \rightarrow (d\mu)_{1/2}$ is less since $\lambda_d(1/2 \rightarrow 3/2)$ also occurs. This reverse transfer would push the expected ratios down.

Table 3

Gamma Ray Yield Ratios if $\lambda d(D_2) =$ 42 x $10^6 S^{-1}$ λd (HD) = 0

Experiment	Expected	Measured
$\frac{Y\gamma(H_2+.50D_2)}{Y\gamma(HD)}$	1.54	$2 \rightarrow 2.2$
$\frac{Y\gamma(H_2+.17D_2)}{Y\gamma(H_2+.52HD)}$	1.3	1.70 ± 0.26

(iii) The other possibility is that $\lambda_{pd\mu-p} \neq \lambda_{pd\mu-d}$ or that $pd\mu$–p preferentially populates $pd\mu$ states J = 0,1,1' and $pd\mu$–d preferentially populates $pd\mu$ states J = 1,1',2.

This possibility (iii) provides a potential explanation of an earlier result by Bleser, et al. (6). They found that in liquid 75% $H_2 + 25\% D_2$ the yield Y_γ was enhanced over saturation by a factor of 1.18. This was taken as evidence for the Wolfenstein-Gershtein effect. However, they used $\lambda_d = 7 \times 10^6/s$! With the modern value $\lambda_d = 42 \times 10^6/s$. they should have seen an enhancement of Y_γ (25% Cd) $= 1.56 * Y_\gamma\,(saturation)$.

Bleser, et al's. results were confirmed in a more recent measurement [(7)]. What causes the discrepancy between the factor measured (1.18) and that predicted (1.56)?

From the description [(6)] of the gas filling technique it appears likely that D_2 and H_2 were simultaneously present in their palladium purifier. This procedure would tend to yield HD as an output along with H_2 and D_2. Hence, based on our results we might conclude that the results of ref. 6 show a smaller than expected fusion gamma ray yield because they had HD in their target and we now know that

$Y_\gamma(HD) < Y_\gamma(H_2 + D_2)$

Temperature Dependence of $pd\mu$ Formation

Still using the conventional model for $pd\mu$ formation we can predict what the $300°K$ gamma yield should be at liquid hydrogen density ($\phi = 1$). Extrapolating from our value ($\phi = .058\phi_o$) and using $\lambda_d = 42\ x\ 10^6/s$ we obtain $Y_\gamma(C_d = 0.17, T = 300K, \phi = 1) = 0.051 \pm 0.015$. But from Bleser, et al's. value at liquid temperature:

$$Y_\gamma(Sat,\ T = 22°K) = 0.14 \pm 0.02$$

and including the enhancement due to Wolfenstein-Gershtein effect $Y_\gamma(Cd = 0.17,\ T = 22°K) = 0.17 \pm 0.02$. There are other corraborating data that point to a temperature dependence listed in Table 4.

Table 4

Comparison of Room Temperature Yields to Liquid Temperature Yields of Fusion Gammarays.

Source	$\lambda_{pd\mu}(10^6 S^{-1})$	T	$Y_\gamma(22°K)/Y_\gamma(300°K)$
ref. 6	5.8 ± 0.3	22°K	
ref. 8	1.8 ± 0.6	300°K	3.2 ± 1.0
ref. 9	2.0 ± 0.5	300°K	2.9 ± 0.7
current data		300°K	3.3 ± 1.0
average			3.1 ± 0.5

The results from Table 3 and ref (1) point to a temperature dependence for the fusion gamma ray from the $pd\mu$ molecule.

Conclusions:

The results reported here are based on about 50% of our new data. We are in the process of analyzing the rest. We draw two surprising conclusions:

$$Y_\gamma(H_2 + D_2) \quad \neq \quad Y_\gamma(HD) \tag{1}$$

$$\frac{Y_\gamma(H_2 + D_2, 22°K)}{Y_\gamma(H_2 + D_2, 300°K)} = 3.1 \pm 0.5 \tag{2}$$

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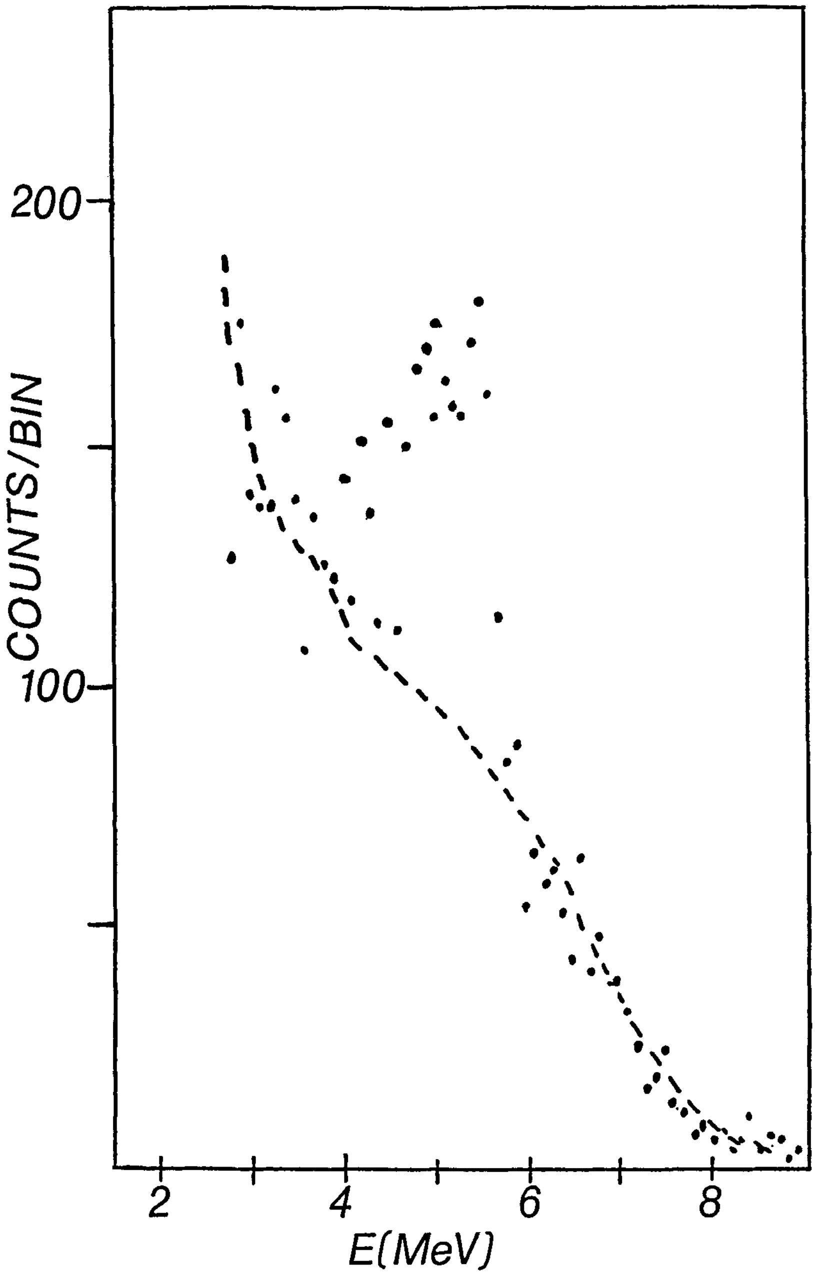

Figure 1: Gamma ray spectrum (dotted) from the $H_2 + D_2 = C(D_2) = 0.17$ target. The background spectrum is shown as the dashed line. The bin size is 0.1 MeV. The gamma ray from the $p + d \rightarrow {}^3He + \gamma$ reaction is visible.

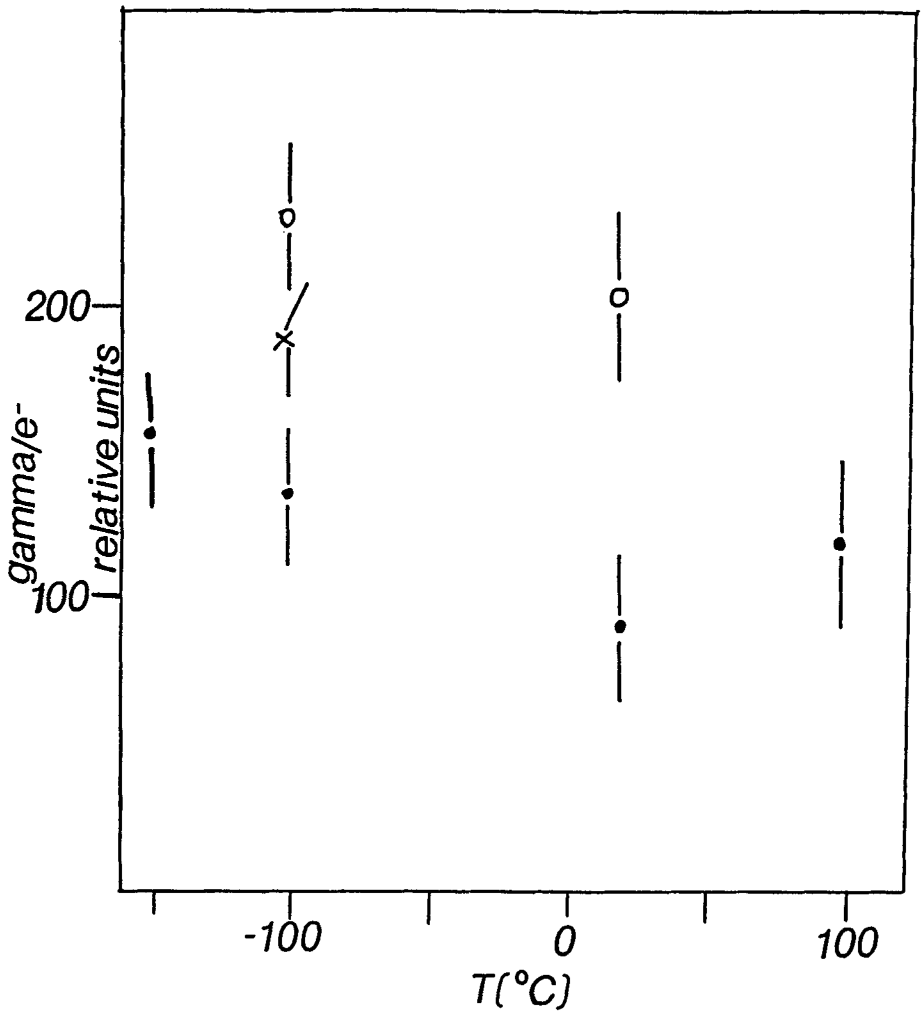

Figure 2: Relative yields of fusion gamma ray/muon decay electrons (arbitrary units). Open circles 0, 83% $H_2 + 17\% D_2$; X , equilibrated mix from above, 56% $H_2 + 38\% HD + 6\% D_2$; closed circles 0, 48% $H_2 + 52\% HD$

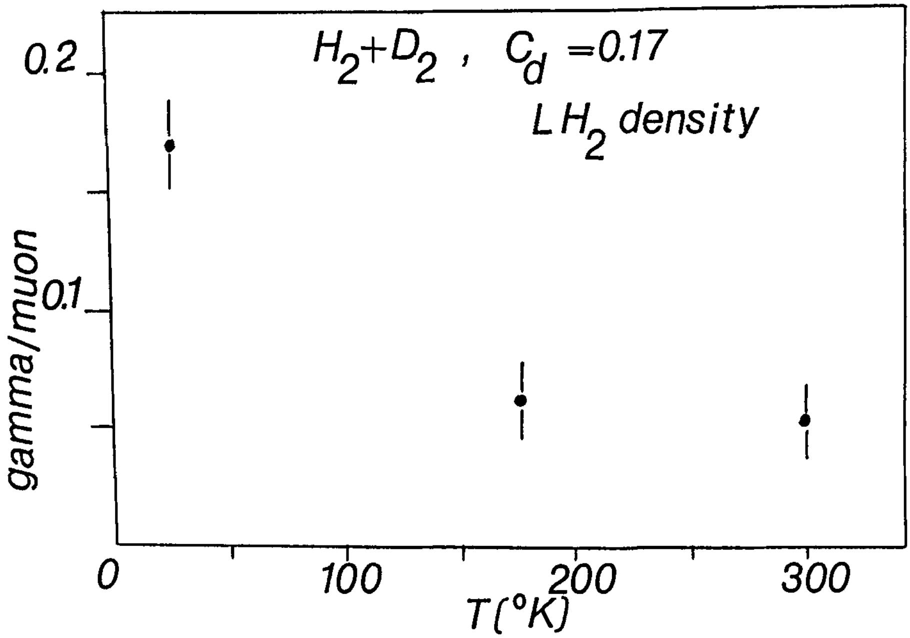

Figure 3: Absolute yield of fusion gamma rays per muon. The points at 173°K and 300° are our new data normalized to liquid hydrogen density using $\lambda_d(\frac{3}{2} \to \frac{1}{2}) = 42\,x\ 10^6\,s^{-1}$. The point at 22°$K$ is scaled value of ref. (6) for a 17% deuterium concentration.