DIRECT MEASUREMENT OF STICKING IN MUON CATALYZED *DT*-FUSION

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The sticking process $dt\mu \rightarrow \alpha\mu + n$ puts the most severe limit to number of fusions which one muon can catalyze in a mixture of hydrogen isotopes. The importance of sticking value for possible practical application of MCF as well as for understanding physical processes involved, determine the interest of experimental groups to measure this quantity. One has to distinguish the initial sticking ω_s^o, as the result of $dt\mu$ fusion, and the final sticking ω_s, observed when the $\alpha\mu$ ion comes to rest. The relation between these quantities is $\omega_s = \omega_s^o(1 - R)$, where the coefficient R reflects all reactivation processes such as excitation, muon exchange and stripping during slow-down of $\alpha\mu$ from the initial energy of 3.57 MeV. Both quantities, ω_s^o and R were intensely recalculated by theoreticians by various methods. The mean value $\omega_s^o(th) = (0.92 \pm 0.01)\%$ was determined with high accuracy, but the reactivation R is not perfectly understood until now since many processes are involved in this phenomenon. It was predicted to vary from 0.28 (at media gas density $\varphi = 0.1$) to 0.35 (at liquid phase) that gives final sticking $\omega_s(th) = (0.61 - 0.66)\%(\pm 0.03)$.

In 1989 the experiment was started at PSI to measure directly the final sticking in muon catalyzed *dt*-fusion. The experimental method was based on an "active target" ionization chamber built at PNPI in Gatchina, and successively for measurement of muon sticking in *dd* fusion [1]. The IC measures pulses of ionization current produced by muons and charged products of fusion reactions ($dt\mu$, $dd\mu$, $pd\mu$, $\cdots$). Neutrons of $dt\mu$ fusion were also detected in coincidence with the IC by the array of scintillator counters, with efficiency $\approx 25\%$ [2]. In 3 experiments, performed during 1989–92, the setup was subjected to improvements, as well as $H/D/T$ gas mixtures (Table) were adjusted to better combination of statistics and energy resolution. The new IC was designed with 3.5 mm thick beryllium entry window, less scattering slow muons, providing up to 1000 muon stops per second in the 3 cm^3 sensitive volume at proton current of 300 μA. In the total about 5 millions of analyzable events were collected.

Table

	C_d, %	D_2, %	HD, %	H_2, %	T_2, %
1989	9.5	1.6	18.8	79.6	0.047
1991	4.0	0.2	7.9	91.9	0.036
1992	3.0	0.1	5.9	94.0	0.036

We used a Flash-ADC readout system in CAMAC environment to detect signals from the anodes of the IC. The data was stored on magnetic tapes and analyzed with special algorithm of pulse recognition in presence of tritium noise. The pulse energy, time of pulse start, duration and other parameters were derived [3]. For analysis of 1992 data the more refined algorithm was used, with higher sensitivity to signal form, very useful for elimination of background. Figs. a, b show the experimental energy spectrum with different selections. The main sources of background in the region of $\alpha\mu$ peak of the energy spectrum are: 1) $t+p$ events of *dd*-fusion, 2) $\alpha\alpha$-pileups caused by finite time resolution of the IC especially in presence of fast catalysis processes, 3) products of muon capture by ^3He, He $\mu \rightarrow t + \nu/d + n + \nu/p + n + n + \nu$, caused by intensive $pd\mu$ catalysis, $pd\mu \rightarrow^3 He\mu + \gamma$, 4) charged particles from muon capture on nitrogen impurity, $\mu N \rightarrow 3\alpha + 2n + \nu$, present in the IC at 1 *ppm* level. The processes 3 and 4 were eliminated by requirement of a delayed coincidence of electron with an IC signal. For analysis of contributions of 1 and 2 a detailed Monte-Carlo calculation was required. Fig. a displays an "ab initio" Monte-Carlo simulation of physics and kinetics of the experiment that was made, starting from generation of ionization charge in 3-D electrostatic field, through charge deposition, signal treatment, and off-line analysis. This spectrum was fitted with assumptions about the theoretical values of initial sticking ω_s^o or of reactivation R, because the events with stripped off muons, $\approx 10\%$, were also under the $\alpha\mu$ peak. These results of fits are:
(a) $\omega_s(exp) = (0.57 \pm 0.03(stat) \pm 0.03(syst))\%$,
with $R = 0.31$ fixed,
(b) $\omega_s(exp) = (0.54 \pm 0.04(stat) \pm 0.03(syst))\%$,
with $\omega_s^o(th) = 0.92\%$(fixed).
According to these fixed parameters the values were obtained for $W_s^o(exp) = (0.83 \pm 0.06)\%$ in (a) and $R(exp) = 0.41 \pm 0.05\%$ in (b).

Another independent analysis of direct evaluation of $\alpha\mu$ was with Monte-Carlo described in [4]. In selection according to the pulse shape, only one parameter, the slope, described in [3], was used. Selection of events with respect to this parameter was justified by measurements with the special test generator, imitating the pulse shapes of real events. In fitting of the energy spectra the number of stripped-off $\alpha\mu$ events was a free parameter, contrary to the first method. The following value was obtained:

$$W_s(exp) = (0.58 \pm 0.03(stat) \pm 0.04(syst))\%$$

The third method used the idea of "survived muon". It requires to select events with two pulses of *dt* fusion caused by one muon in the IC. In these events the muon is obviously not trapped in the first fusion, and is not lost otherwise. The observed spectrum is therefore free from "final sticking" events. The single fusion spectrum, normalized to the same intensity of alphas, is shown in fig. b with dashed line and with points. This method provides really pure and direct measurement of final sticking ω_s, independent of stripping theory. The result is

$$\omega_s(exp) = (0.57 \pm 0.07(stat) \pm 0.02(syst))\%$$

Averaging the obtained values of ω_s, we can present the current result as $\omega_s(exp) = (0.56 \pm 0.04)\%$, which is 2 standard deviations less than the theoretical prediction:

$$\omega_s(th) = (0.65 \pm 0.03)\%.$$

In conclusion, we can say that $\alpha\mu$ sticking ω_s in $dt\mu$ fusion was for the first time directly observed. The value is now established to be slightly lower than the theory, limiting possible fusion output of MCF to a value 200 per muon.

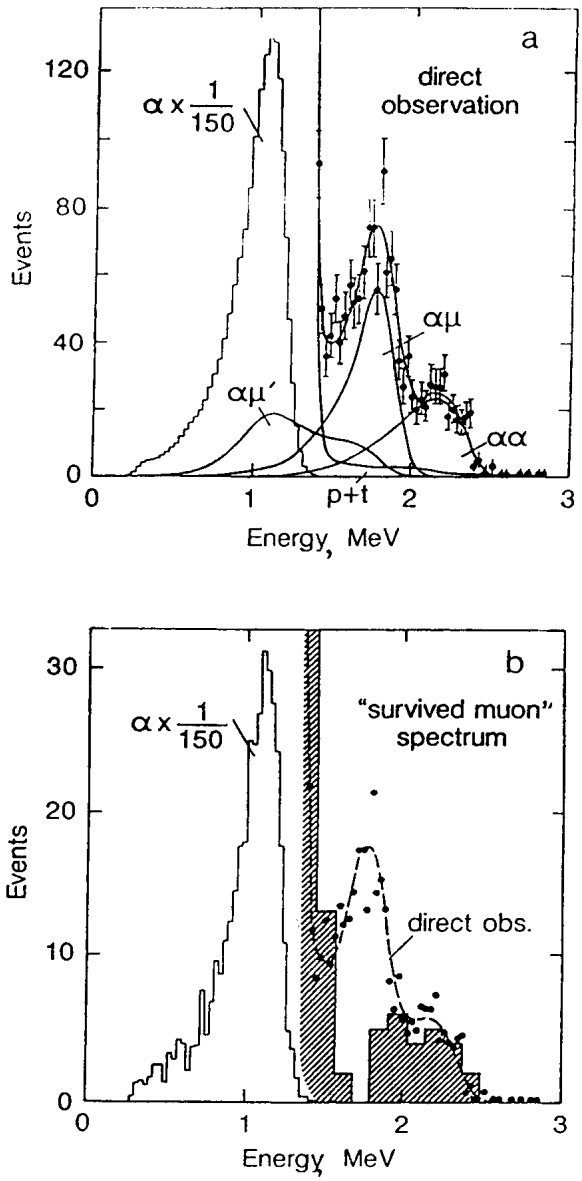

Fig. The data of 1992 experiment.
(a) — The direct observation. In the higher energy region the peaks of $\alpha\mu$, reactivated $\alpha\mu$ and $\alpha\alpha$ pileups are displayed. (b) — "survived muon" method. Only the first fusions from the double-fusion events are considered in this plot. Therefore the sticking peak is absent

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