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Measuring sticking and stripping in muon catalyzed *dt* fusion with multilayer thin films

M.C. Fujiwara[1,*], J.M. Bailey[2], G.A. Beer[3], J.L. Beveridge[4], E. Gete[1] T.M. Huber[5],
R. Jacot-Guillarmod[6], P. Kammel[7], N.P. Kherani[8], S.K. Kim[9], P.E. Knowles[3],
A.R. Kunselman[10], V.E. Markushin[11] G.M. Marshall[4], C.J. Martoff[12], G.R. Mason[3],
F. Mulhauser[4,†], A. Olin[3], C. Petitjean[13], T.A. Porcelli[3], T.J. Stocki[1], and J. Zmeskal[14]

[1] *University of British Columbia, Vancouver, British Columbia, V6T 2A6 Canada*

[2] *Chester Technology, Chester, UK*

[3] *University of Victoria, Victoria, British Columbia, V8W 2Y2 Canada*

[4] *TRIUMF, Vancouver, British Columbia, V6T 2A3 Canada*

[5] *Gustavus Adolphus College, St. Peter, MN 56082, USA*

[6] *Université de Fribourg, CH-1700 Fribourg, Switzerland*

[7] *Lawrence Berkeley Laboratory, Berkeley, CA 94720, USA*

[8] *Ontario Hydro, Toronto, ON, M8Z 5S4, Canada*

[9] *Jeonbuk National University, Jeonju City 560-756, S. Korea*

[10] *University of Wyoming, Laramie, WY 82071, USA*

[11] *Russian Research Center, Kurchatov Institute, Moscow, 123182, Russia*

[12] *Temple University, Philadelphia, PA 19122, USA*

[13] *Paul Scherrer Institute, CH-5232 Villigen, Switzerland*

[14] *Austrian Academy of Sciences, A-1090 Wien, Austria*

We propose a direct measurement of muon sticking to alpha particles in muon catalyzed *dt* fusion at a high density. Exploiting the features of a multilayer thin film target developed at TRIUMF, the sticking is determined directly by detection of charged fusion products. Experimental separation of initial sticking and stripping may become possible for the first time. Monte Carlo simulations, as well as preliminary results of test measurements are described.

[*] electronic mail: fujiwara@triumf.ca

[†] Present address: Université de Fribourg, CH-1700 Fribourg, Switzerland

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1 Motivation

Sticking, the probability of the process in which the muon gets attached to the alpha particle (α) after fusion, is undoubtedly one of the most important parameters in muon catalyzed fusion, since it limits the fusion yield per muon. Despite great efforts over more than a decade, discrepancies between experiment and theory persist, the former being systematically lower than the latter.

The recent theoretical calculations of initial sticking, which take into account such effects as nuclear structure [1] and deviations from the sudden approximation [2], have converged to agree within a few percent. The predictions, however, cannot not be readily compared with experiment, because all the previous experiments (with exception of pioneering, but still preliminary measurements [3]) are primarily sensitive to the final sticking, which is a combination of two separate processes; *initial sticking*, the intrinsic branching ratio for $d\mu t \rightarrow \mu\alpha$ (muonic helium ion) $+n$, and *stripping*, in which the muon is detached from the α in collisions with the target atoms. It appears that there is little room for improvement in the calculation of both initial sticking and stripping [4] within the current theoretical framework. New experimental insight is urgently required.

A recent experiment at PSI has shown that detection of charged fusion products ($\alpha/\mu\alpha$) gives the most direct, high accuracy measurement of sticking [5]. However, no results using this method are available at high densities, at which indirect neutron measurements give value about a 30% (3σ) lower value than theory. For a comparison of different methods of sticking measurement, see a recent review [5][1].

Given this situation, we feel that there is a strong motivation for the following tasks, 1) experimental separation of initial sticking and stripping, and 2) a direct measurement of sticking at a high density. We will describe in this paper a method of a new sticking measurement which addresses these issues, with emphasis on two recent independent proposals [8,9] which exploit characteristics of the TRIUMF multilayer film target.

2 Experimental Concept

Shown in Fig. 1 is a conceptual drawing of the proposed experiment. The target system is based on the one described in Ref. [10,11], and only minor modifications are required. The muon stopped in a layer of protium with $c_t \sim 10^{-3}$ (*emitter*) is

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[1] For most recent progress of other sticking experiments, see Ref. [6,7]

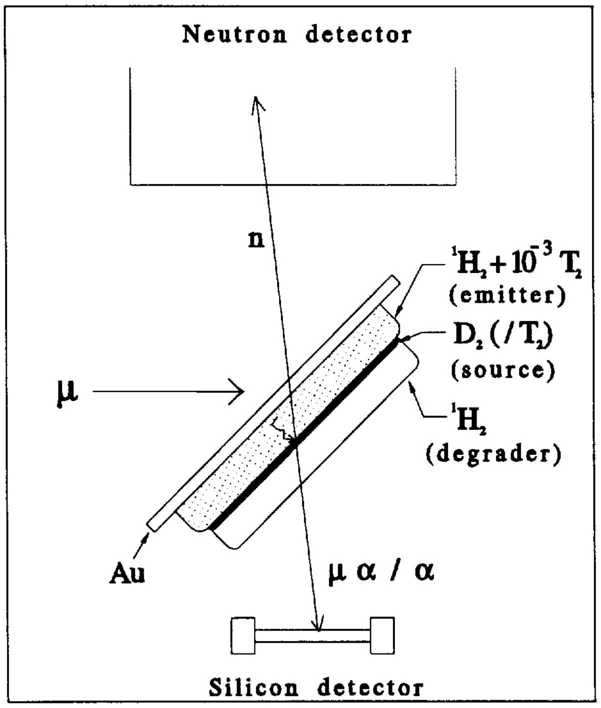

Figure 1: Conceptual drawing of the proposed experiment.

converted into μt, which is then emitted via the Ramsauer-Townsend effect. The μt enters the adjacent deuterium layer (*source*) in which molecular formation and fusion take place. The third layer made of protium (*degrader*) separates the α and the $\mu\alpha$ by the difference in the stopping powers, since dE/dx is roughly proportional to the Z^2 of the projectile. The charged products are detected directly with a silicon detector. Detection of the fusion neutron is useful for background rejection with $\alpha/\mu\alpha$–n collinear (back-to-back) coincidence, as well as for normalization.

The direct observable in this method is $\omega_s^{eff}(l)$, the $\mu\alpha/(\mu\alpha+\alpha)$ ratio as a function of the $\mu\alpha$ path length, which is defined as

$$\omega_s^{eff}(l) \equiv \omega_s^0[1 - R^{eff}(l)], \tag{1}$$

where $R^{eff}(l)$ is the probability that stripping occurs by the time $\mu\alpha$ travels a distance l in the target medium, and l is determined from the target thickness and geometry. When a thin degrader and source, hence a small l is used, the method will be sensitive to initial sticking, since only a small correction R^{eff} is required. By changing the thickness of the degrader, a systematic measurement of stripping as a function of $\mu\alpha$ energy can be performed. Thus, experimental separation of initial sticking and stripping will be possible in principle.

Table 1: Comparison of characteristics between the proposed multilayer cold film (MCF) method and the homogeneous gas target experiment [3]. The quoted numbers are approximate.

	gas experiment	MCF method
μt production	entire target	emitter
mol. formation, fusion	entire target ($1\,\mathrm{mg{\cdot}cm^{-2}}$)	source ($0.1\,\mathrm{mg{\cdot}cm^{-2}}$)
energy loss, stripping	entire target, windows, buffer gases[2]	degrader[3]
μ^- stopping in target[4]	1%	30%
fusion yield/incident μ^-	2×10^{-3}	2×10^{-2}(×cycling)
T_2 content	750 Ci	10 Ci

[1] Necessary to protect the Si detector from tritium activity.
[2] Energy loss and stripping in the source is small.
[3] Relevant for background induced by μ^- stop in target frame.

The philosophical advantage of the proposed method lies in the heterogeneous structure of the target. The key steps in μCF such as μ^- stop $\rightarrow$ μt production, molecular formation and fusion, and $\mu\alpha(\alpha)$ slowing and stripping, are spatially confined in the each layer, and can be controlled on individual basis. The use of the emitter layer permits a thin layer as the source, which provides $\mu\alpha$ and α of well-defined energies, while achieving a muon stopping rate which is much higher than the thin source layer by itself can provide. Minimizing the broadening of the initial energy distribution is essential in order to achieve good energy separation of the $\mu\alpha$ and the α. Also, slowing and stripping which take place in the degrader are decoupled from the other processes, and can be controlled without affecting the kinetics leading to fusion. Thus, the hetero-structure nature of the target enables engineering of muonic processes for specific purposes.

This is in sharp contrast to a similar experiment using a homogenous gas target [3], where most of the processes were inevitably interconnected. The fusion and the subsequent energy loss occurred in the entire target, which had to be rather thick to provide sufficient muon stops. As a result of the spatially ill-defined reactions, broadening of $\mu\alpha$ and α energy distributions was very large, preventing a clear separation of the two peaks. Stripping as well as energy loss could be controlled to some extent by varying the target gas density, but this affected the entire kinetics in a highly non-linear manner, leading to normalization problems. Furthermore, the use of a solid target in the proposed method removes the need for target windows. The Si detector protection is not necessary, due to a low inventory of tritium and its low diffusivity at low temperature. Both the windows and Si protection needed in experiment [3] caused not only the uncontrollable stripping, but also significant background. The comparison is summarized in Table 1.

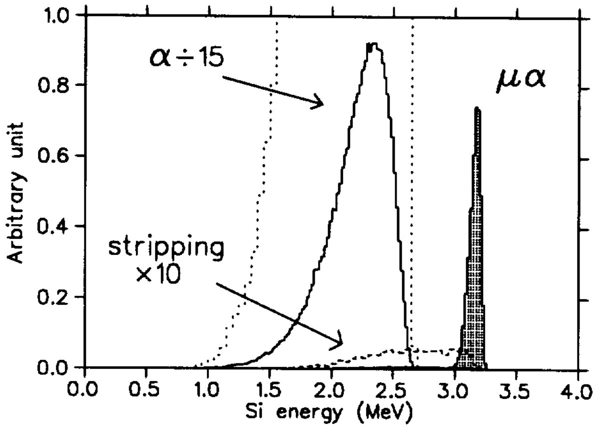

Figure 2: A typical result of Monte Carlo simulations. The dotted line is the α peak, while the solid line shows it reduced by 15 for comparison. Events from stripping which occur in the target are magnified by 10.

3 Monte Carlo Simulations

In order to examine the feasibility of the experiment, Monte Carlo simulations were performed. The detector energy resolution, $\alpha(\mu\alpha)$ energy straggling, and the target non-uniformity were neglected in the present calculations, while the $\mu\alpha$ stripping cross sections were taken from Ref. [12]. The details of the simulations can be found in Ref. [9].

Figure 2 shows a typical result of the calculations. Three types of events in the Si detector energy spectrum are plotted; α events, $\mu\alpha$ events, and stripping events that occur in the target (mostly in the degrader). For comparison, the solid line shows the α peak reduced by a factor of 15, and stripping is magnified by 10. The both α and $\mu\alpha$ peaks are clearly separated with their energies well above the detection threshold. In this case, determination of $\omega_s^{eff}(l)$ is very direct. Furthermore, the initial sticking can be deduced from

$$\omega_s^0 = \omega_s^{eff}/(1 - R^{eff}). \tag{2}$$

The correction due to stripping in the target layers R^{eff} is estimated to be a few percent under the conditions optimized for the initial sticking measurement.

It is interesting to note that the $\mu\alpha$ peak is intrinsically narrower than the α peak due to a smaller dE/dx, resulting in easier separation. This is in contrast with the PSI direct measurement where the $\mu\alpha$ peak was comparable to or wider than the α [5].

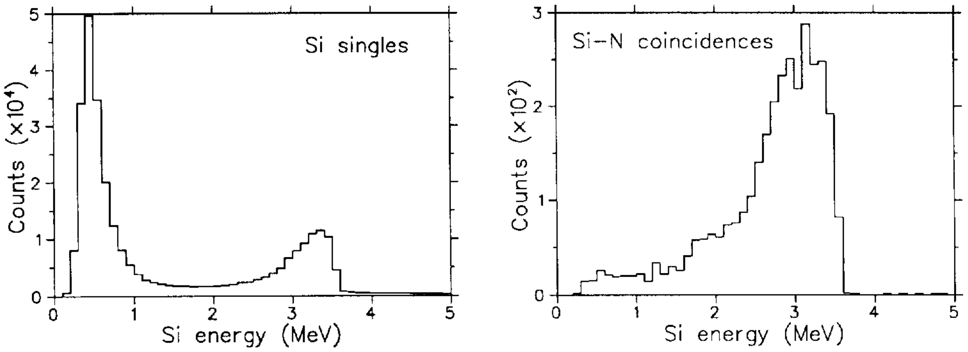

Figure 3: Silicon detector energy spectra without degrader. The measurements with and without the α–n collinear coincidence condition are compared.

Even in a rather pessimistic scenario where the peak broadening is too large for observation of both peaks in a single spectrum, an accurate determination of ω_s^{eff} is still possible by combining separate measurements. In a measurement without degrader, the sum of α and $\mu\alpha$ events is counted in the Si spectrum. In the subsequent measurement with a thick degrader to range out the α, $\mu\alpha$ events are recorded. Sticking can then be determined from the ratio of the two counts normalized to the simultaneously recorded singles (*i.e.* without α coincidence) fusion neutrons. Because the detector efficiencies in the two measurements are nearly the same, and because normalization to the singles neutrons cancels any changes in the target conditions between the measurements (to first order), this method also gives a precise determination of sticking. In fact, it provides a redundancy in the analysis for measurements illustrated in Fig. 2.

4 Preliminary measurements

A preliminary experiment was recently performed to test the method. The apparatus was identical to that given in Ref. [13,14] since the test was done as a parasitic measurement. It should be emphasized that the target geometry as well as detector arrangement was *far* from optimal, and data were taken only for a few hours. The difficulties included the peak broadening due to the unfavourable angles of the the $\alpha(\mu\alpha)$ path, and the small acceptance for collinear coincidence detection.

The data taken with the target without degrader are shown in Fig. 3. Silicon detector energy spectra are compared with and without the collinear neutron coincidence condition. This clearly illustrates the power of the coincidence technique, with the large background at low energy strongly suppressed. The Si detector had

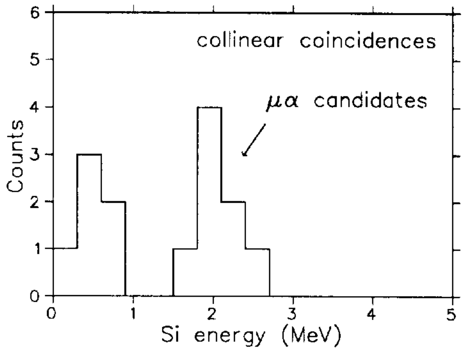

Figure 4: Test measurement with H_2 degrader 250 μg·cm^{-2}. The peak indicated has an energy consistent with $\mu\alpha$ events.

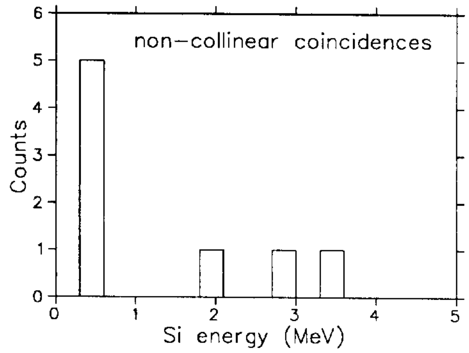

Figure 5: Coincidence between non-collinear detector pair was taken for the background estimation.

typically several ns time resolution. Notice that even without any degrader, the broadening of the peak is very large compared to the detector energy resolution of ~65 keV (at 5.5 MeV) due to non-optimal geometry.

Another measurement was made with approximately 250 μg·cm^{-2} protium degrader, which, with average angle of about 80 degrees, should be sufficient to range out the α. Figure 4 shows a Si energy spectrum with the collinear neutron coincidence condition. A peak is observed near 2 MeV which is consistent with the expected energy of a $\mu\alpha$ penetrating the degrader. Figure 5 shows a spectrum of a detector pair which is located non-collinearly, giving an estimate of the background. Despite the poor conditions, we have an indication of the first direct observation of sticking in solids.

5 Discussion

The sensitivity to initial sticking is determined by the experimental energy separation of the $\mu\alpha$ and the α. With better resolution, thinner degraders can be used, minimizing the correction due to stripping. Simulations with the various conditions indicate that the energy resolution may be limited by variations in α and $\mu\alpha$ path length due to the finite size of the beam and detectors. The use of smaller detector can increase the resolution at the expense of statistical precision. Alternatively, segmentation of neutron and/or charged particle detectors could improve the sensitivity without this expense. Another limitation may come from non-uniformity of the layers found in Ref. [9,15]. Further Monte Carlo studies are in progress.

When the $\mu\alpha$ is stopped in a Si detector, the muon can be stripped (via both ionization and transfer) with a high probability [16], and μ^- capture on the Si nucleus may occur, producing some charged events [17]. This could pile up with the original $\mu\alpha$ signal, and distort the $\mu\alpha$ spectrum in the Si detector. Since the α events are lower in energy, the piled-up $\mu\alpha$ events fortunately do not overlap with them, but its possible influence on the efficiency for the $\mu\alpha$ detection has to be taken into account in the analysis in order to achieve an accurate measurement.

The rate for $\mu\alpha$-n coincidence events *without* cycling is estimated to be of order $\sim 3 \times 10^{-3}\,\mathrm{s}^{-1}$ ($\sim$ 10 events per hour) for the apparatus similar to the test measurement with required modifications, which may give a somewhat larger peak broadening compared to Fig. 2. The event rate may be significantly enhanced by the use of a D–T mixture in the source layer, which would allow recycling of the muon. Muon loss due to escape of μt or μ^- [18] from the layer may limit cycling. In fact, cycling in thin films is an intrinsically interesting subject, as well as being important for the proposed experiment, so Monte Carlo studies in D_2 films [19] will be extended to D–T, and measurements are planned to test the predictions. For thick degrader measurements, protium with $c_t \sim 10^{-3}$ can be used as degrader, which can at the same time emit μt back into the source layer, resulting in the increase of fusion yield.

Many new measurements can be considered as an extension of the proposed experiment, but only a few are mentioned here. Immediately possible, after some success in the sticking experiment, may be the systematic investigation of $\mu\alpha$ stripping in other elements. For example, neon can be readily frozen on top of hydrogen layers for this purpose. In fact, the measurement should be easier than measuring the stripping in hydrogen due to a larger ratio of cross sections for stripping to energy loss [16]. Alternatively, assuming the theoretical stripping in neon, ω_s^0 can be deduced from the data, providing a rather independent check of initial sticking.

A "beam" of $\mu\alpha$ with rather well defined energy can be obtained with the thick degrader setup. This would be complementary in energy to the μHe beam proposed in Ref. [20]. The study of resonance states in the dμHe molecule may become possible [21].

Another application of the proposed apparatus is calibration of the neutron detector using the α–n coincidence. In the geometry where all the α associated with registered neutron events can be detected, absolute efficiency of the neutron detection system can be measured, provided the Si detector solid angle is known. We are considering the possibility of a precision measurement of the μ^- transfer rate λ_{dt} and/or molecular formation rate $\lambda_{dt\mu}$ in solid at 3 K with the calibrated neutron detectors. The latter, in particular, addresses the current theoretical controversies such as the question of subthreshold resonances due to many-body effects [22,23] or finite resonance width [24], as well as thermalization of μt in a solid [25]. The neutron measurement in a solid H/D/T mixture is also an interesting possibility.

In conclusion, we have shown that the TRIUMF multilayer film target can be used for the direct measurement of sticking, in which we hope to obtain detailed information on sticking and stripping in a high density environment. A formal research proposal has been recently submitted to TRIUMF [26].

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References

[1] J. S. Cohen *et al.*, proceedings of this conference, and references therein.
[2] V. S. Melezhik, proceedings of this conference.
[3] S. E. Jones *et al.*, AIP Conf. Proc. **181**, 2 (1989), J. D. Davies *et al.*, J. Phys. G **16**, 1529 (1990).
[4] C. D. Stodden *et al.*, Phys. Rev. A **41**, 1281 (1990).
[5] C. Petitjean *et al.*, Hyp. int. **82**, 273 (1993).
[6] D.L. Demin *et al.*, proceedings of this conference.
[7] K. Nagamine *et al.*, proceedings of this conference.
[8] P. Kammel, private communication.
[9] M. C. Fujiwara, Master's thesis, University of British Columbia, unpublished (1994).
[10] P. E. Knowles *et al.*, Hyp. Int. **82**, 521 (1993).
[11] P. E. Knowles *et al.*, to be published in Nucl. Instr. Meth. A.
[12] V. E. Markushin, Muon Catalyzed Fusion **3**, 395 (1988).
[13] G. M. Marshall *et al.*, proceedings of this conference.
[14] F. Mulhauser *et al.*, submitted to Phys. Rev. A.
[15] M. C. Fujiwara *et al.*, proceedings of this conference.
[16] J. S. Cohen, Phys. Rev. A **37**, 2343 (1988).
[17] S. E. Sobottka and E. L. Wills, Phys. Rev. Lett. **20**, 596 (1968).
[18] K. Nagamine, Proc. Japan Academy **65**, 225 (1989).
[19] T. A. Porcelli *et al.*, poster presentation at this conference.
[20] K. Nagamine, Hyp. Int. **82**, 343 (1993).
[21] C. Y. Hu *et al.*, Phys. Rev. A **42**, 5769 (1990).
[22] M. Leon, Hyp. Int. **82**, 151 (1993).
[23] K. Fukushima, Phys. Rev. A **48**, 4130 (1993).
[24] Yu. V. Petrov *et al.*, Phys. Lett. B **331**, 266 (1994).
[25] A. Adamczak, proceedings of this conference.
[26] M.C. Fujiwara *et al.*, TRIUMF Research Proposal, Experiment 767.