USING THIN FILM TARGETS FOR MUONIC ATOMS AND MUON CATALYZED FUSION STUDIES

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Studies of muonic atoms and muon catalyzed fusion have been conventionally done in a bulk target of gas, liquid or solid hydrogen isotopes. The use of thin film targets developed at TRIUMF have notable advantages in tackling some of the most important questions in the field, which could be further exploited at future high intensity muon sources. We review the technique of the thin film method with emphasis on recent results and a future proposal.

1 Introduction

A negative muon can participate in a variety of atomic and molecular processes. When it is introduced into a target, a muonic atom is readily created replacing an electron, which can then form a muonic molecule. The latter in turn can result in fusion reactions between the nuclei if the target consists of hydrogen isotopes, a phenomenon known as muon catalyzed fusion ($\mu$CF).

The use of a thin target in muon physics experiments has some notable advantages. One general (and obvious) advantage is that it allows, with high energy resolution, the detection of out-going particles of the reaction, e.g. $\alpha$ particles from fusion, or possibly electrons from $\mu-e$ conversion. Using thin

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film targets, held in a vacuum without a window, offers additional merits in muonic atom studies. When the layer thickness is small compared to the range of the atom in that medium, it can be extracted from the layer, producing a beam of muonic atoms in vacuum. This allows to isolate the process of interest from the rest of the reaction chains, offering unique advantages over conventional targets in which usually complex and interconnected processes take place. There exist some disadvantages of thin film methods which include limited statistics due to the small fraction of muon stopping in the thin films, and increased background from the large fraction muon stopping in the target support and the chamber.

New high intensity muon sources, now being actively investigated worldwide, could enhance greatly the advantages of thin targets while alleviating their disadvantages. In this articles, we review the thin film method and discuss recent results and a future proposal in muonic atom and muon catalyzed fusion experiments at TRIUMF.

2 Muonic hydrogen atom beams from thin films

The basic processes involved in creating a beam of muonic hydrogen atoms can be categorized into four steps: atomic formation, acceleration, extraction, and moderation. Let us take as an example the production of muonic tritium atom (µt) beam. When a muon is stopped in a thin solid hydrogen target consisting of protium (1H2) doped with a small amount (εt ∼ 0.1%) of tritium, muonic protium atom (µp) is mostly formed (atomic formation). The muon quickly transfers from proton to triton to form µt, the latter more tightly bound due to the reduced mass difference. In the reaction, the µt gains about 45 eV of recoil kinetic energy, and is thus accelerated. The µt then slow down from the collisions with the rest of the target nuclei (mostly protons), until it reaches about 10 eV. At these energies, µt + p elastic scattering cross section drops dramatically due to a phenomenon known as the Ramsauer-Townsend effect, making the rest of the target nearly transparent. The µt atom is thus extracted from the layer into vacuum. The energy of the emitted µt can be controlled to some extent by placing an additional layer, for example of deuterium, on top of the emission layer (moderation). Creation of muonic deuterium (µd) is possible in a similar manner with a deuterium-doped protium target: in fact, the emission of muonic hydrogen atoms was first discovered in this system.

Unexpected emission of µp from a pure 1H2 target was observed recently, which indicates the existence of unconventional acceleration and extraction.

\(^\text{4}^\text{Elastic scattering cross section goes to zero, when the s-wave phase shift goes to } \pi \text{ and the contributions from higher partial waves are negligible.}\)
mechanism. Presumably, \(\mu p\) is accelerated during the atomic cascade to the ground state, while \(\mu p\) extraction from the layer may be enhanced due to the condensed matter effects in \(\mu p + p\) scattering. The energy of emitted \(\mu p\), though it has not been directly measured, is expected to be of order \(\sim\text{meV}\) given by the Bragg cut-off limit, and its hyperfine state to be in \(F = 0\) due to the high spin exchange rate in the target.

These observations of \(\mu p\), \(\mu d\), and \(\mu t\) emission are not only useful for new type of experiments, but also interesting in its own right in testing the quantum few body calculations. Because of the large mass of the muon, comparable to that of nuclei, reactions of muonic atoms is non-adiabatic in nature, and the corrections due to relativistic and QED effects may be non-negligible in some cases. Measurements reported up to now by the TRIUMF group include, charge exchange processes \(\mu p + d \rightarrow p + \mu d, \mu p + t \rightarrow p + \mu t\); elastic scattering processes \(\mu d + p \rightarrow \mu d + p, \mu t + p \rightarrow \mu t + p\); spin exchange processes \(\mu d^F = \frac{1}{2} + d \rightarrow \mu d^F = \frac{3}{2} + d\); molecular formation \(\mu p, d \mu d\); and the astrophysical \(S\) factor from \(p \mu d\) fusion. Many of these processes play important roles in \(\mu CF\) as well as in other fundamental muon physics experiments. In the following sections, we focus on two crucial processes, \(d \mu t\) formation and \(\mu -\alpha\) sticking.

3 Resonant molecular formation in \(\mu CF\)

Muon catalyzed fusion in the deuterium-tritium system currently has two major bottle-necks in term of achieving high efficiency. One is the rate at which a muon can go through the catalysis cycle (cycling rate), and another is a poisoning process called \(\mu -\alpha\) sticking in which, with a probability \(\omega_s \sim 0.005\), the muon gets captured to atomic bound states of the fusion product \(^4\text{He}\) after the fusion reaction, and hence lost from the cycle (see Section 4). The former is limited mainly by the rate of formation of muonic molecule \(d \mu t\). In fact, a straightforward mechanism for molecular formation via Auger process is much too slow, yielding the fusion efficiency of the order of only one fusion per muon. A resonant mechanism, however, can give much higher rates when the certain condition is satisfied. In the resonant formation, \(\mu t + D_2 \rightarrow [(d\mu t)dec]_{\nu K}\), the reaction product is a hydrogen-like molecular complex \([(d\mu t)dec]\) in which \((d\mu t)^+\) plays a role of one of the nuclei. The process is resonant, because the energy released upon formation of \(d\mu t\) plus the \(\mu t\) kinetic energy has to coincide the ro-vibrational \((\nu K)\) excitation spectrum of \([(d\mu t)dec]\) in the final state. This is only possible due to the existence of a state in \(d\mu t\) which is bound very loosely (in the muonic scale) with the binding energy smaller than the dissociation energy of deuterium molecules.

Theoretical calculations predict strong enhancement of the formation
rate $\lambda_{d\mu t}$ at $\mu t$ energy of order 1 eV, but direct experimental information on such epithermal resonance is scarce. In conventional $\mu$CF experiments, determination of $\lambda_{d\mu t}$ is rather indirect and model dependent due to the complexity of muonic reaction cycles in the target. As well, the resonant energies $\sim$ 1 eV is difficult to access with the target thermal energy, since it would require a target of several thousand degrees, a formidable task when working with tritium. The use of $\mu t$ beam provides some unique advantages in this case: (1) formation process can be isolated, to large extent, from the rest of the cycle, (2) epithermal energies are directly accessible due to the available beam energy, and (3) $\mu t$ time of flight across the drift distance provide information of the resonance energies.

Figure 1 (a) illustrates the principle of our method. A beam of $5 \times 10^3 \mu^-/s$ of momentum 27 MeV/c from the TRIUMF M20B channel was degraded in a 51 $\mu$m gold target support, and stopped in the upstream (US) emission layer. The $\mu t$ beam, obtained as described above, were slowed via elastic scattering in a D$_2$ moderation layer from some 10 eV to near 1 eV to better match the resonance energies. The $\mu t$, after a few $\mu$s time of flight (TOF), is collided with a reaction layer in downstream (DS), separated by the drift distance of 17.9 mm in vacuum. Formation of $d\mu t$ molecules is detected by observing 3.5 MeV $\alpha$ particles produced in the fusion reaction, $d + t \rightarrow \alpha + n$, which follows

![Figure 1: (a) Schematic of the thin film target for the $d\mu t$ formation measurements consisting of the emission, the moderation and the reaction layers, which are prepared by rapidly freezing hydrogen isotopes on the gold foils (not shown) held in vacuum at 3.5 K. The layer thickness (3.43 mg·cm$^{-2}$, 96 $\mu$g·cm$^{-2}$, and 21 $\mu$g·cm$^{-2}$, respectively) were measured off-line via $\alpha$ particle energy loss. (b) Measured Si energy spectra with prompt (I: $t > 0.02 \mu$s) and delayed (II: $t > 1.5 \mu$s) time cuts. Fusion in DS reaction layer is separated from that in US D$_2$ due to the $\mu t$ TOF across the vacuum.](image_url)
Figure 2: Time-of-flight fusion spectrum (error bars) and simulation spectrum (histogram), normalized the number of incident muons $N_{\mu}$. Also plotted are simulated contributions from different resonance peaks given by the time–energy correlated events.

the formation. Si detectors placed in the vacuum enables the measurement $\alpha$ with high energy resolution. The background can be determined accurately by “turning off” the DS fusion reactions using the target without the DS layer. This ability to control a specific process, without affecting the rest, is an advantage of the thin film method. (In conventional targets, changing the target conditions would affect many processes simultaneously).

Because the time between muon stop and the fusion $\alpha$ detection is dominated by the $\mu t$ TOF, it provides a measure on molecular formation energy, as long as the energy loss of $\mu t$, due to elastic scattering before the formation in the DS D$_2$, is small. A thin DS layer (~1 $\mu$m) was necessary to minimize this energy loss so as not to obscure the time-energy correlation.

The detail of our analysis can be found Refs. and here we give the resulting DS fusion time spectrum and its comparison with Monte Carlo (MC) simulations in Fig. 2, which clearly establishes the resonance structure. From the time-of-flight analysis of $2036 \pm 116$ DS fusion events, a formation rate consistent with $0.73 \pm 0.16_{\text{meas}} \pm 0.09_{\text{model}}$ times the theoretical prediction of Faifman et al. was obtained (the first error refers to the measurement uncertainty including the statistics and the second is that in MC modeling). The resonance energies were determined from the fit to be $0.940 \pm 0.036_{\text{meas}} \pm 0.080_{\text{model}}$ times the theory. Thus, for the first time, the existence of epithermal resonances in $d\mu t$ molecular formation was directly confirmed, and their energies measured. For the largest peak at the reso-
nance energy of $0.423 \pm 0.037$ eV, our results correspond to the peak rate of $(7.1 \pm 1.8) \times 10^9$ s$^{-1}$. This is more than an order of magnitude larger than the rates at lower energies, experimentally demonstrating the prospect for high cycling $\mu$CF in a high temperature target of several thousand degrees. If one assumes the energy levels of the $[(d\mu)t \bar{e}]$ molecule, which have a similar structure to those of ordinary hydrogen, our results imply sensitivity to the binding of energy of the loosely bound $(d\mu)t_{11}$ state with an accuracy comparable to the vacuum polarization and other QED corrections, opening up a new possibility of precision spectroscopy in a quantum few body system.

The data have been subsequently collected for $d\mu t$ formation in the $\mu t + HD$ collision, for which for stronger resonances at lower energies are predicted. This will be reported in a future publication.

4 Direct measurement of $\mu-\alpha$ sticking

The process of $\mu-\alpha$ sticking gives a stringent limit, independent of the cycling rate, on the number of fusions catalyzed by one muon. As such, great efforts have been made for nearly two decades to understand this process, but discrepancies persist between and theory and experiment (including latest PSI and RIKEN-RAL results), the latter being systematically lower than the former.

Calculations of sticking are challenging, due to the interplay of the Coulomb and strong interactions in a non-adiabatic few-body system, yet recent predictions, including the effects of nuclear structure and the deviations from the standard sudden approximation, They cannot, however, be readily compared to experiment because most measurements are primarily sensitive to final sticking ($\omega_{\text{fin}}^0$), which is a combination of initial sticking ($\omega_{\text{ini}}^0$), the intrinsic branching ratio for $d\mu t \rightarrow \mu \alpha + n$, and stripping ($R$), collisional reactivation of the muon from $\mu \alpha$ in the target medium (i.e., $\omega_{\text{fin}}^0 \equiv \omega_{\text{ini}}^0 (1 - R)$).

Confusing history of experimental sticking results has been in part attributed to the difficulties associated with the conventional neutron method, which include a high model dependence and the need for the absolute neutron calibration. A recent RIKEN-RAL experiment has directly observed, with impressive statistics, X-rays from $\mu \alpha$ deexcitation, taking advantage of the new intense pulsed muon beam which enabled the large signal enhancement, but unfortunately the determination of the sticking probability has to rely on the models of $\mu \alpha$ cascade and stripping, which are yet largely untested.

We propose a new direct experiment of sticking using multi-layer thin film targets. The method is illustrated in Fig 3, and the details are given in Refs.\textsuperscript{25,26}.

\textsuperscript{d}Upon sticking a fraction of the muon gets captured into excited atomic states of $\mu \alpha$ and can emit X-rays if it deexcites to the ground state.
(a) The $\mu$ created in the emitter is stopped in the source, where fusion takes place producing $\alpha^{++}$ or $(\mu\alpha)^+$. The degrader separates the two species by their stopping powers (recall that $dE/dx \propto Z^2$). Collinear coincidence of the neutron with the charged events suppresses the background. (b) Simulated Si spectrum for the coincidence events, showing a clear separation between $\alpha$ and $\mu\alpha$ peaks.

The determination of sticking from the ratio $\mu\alpha/(\mu\alpha + \alpha)$ is simple and model independent. Since the stripping in the degrader is small, the measurement is sensitive to the initial sticking, while the stripping itself process can be systematically studied by varying the degrader thickness. Thus experimental separation of initial sticking and stripping will become possible for the first time. The use of very thin (< few $\mu$m) source layer is essential for minimizing the peak broadening in order to achieve good energy separation of the $\mu\alpha$ and $\alpha$. The expected precision of $\sim 5\%$ in initial sticking is limited by the statistics.

5 Summary

The thin film methods have yielded unique results in the studies of muonic atoms and muon catalyzed fusion, and offer opportunities for more new experiments. These measurements, because of their thin targets, could further
benefit from the advent of high intensity, high quality muon sources.

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