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Muon Catalyzed Fusion at Very Low Temperature : A New Target System

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Muon catalyzed fusion (μCF) processes are usually studied in gases or liquids. A new target system allows experiments on muonic hydrogen isotopes in solid hydrogen layers at 3K, where processes of the μCF cycle can be separated and the energy dependence of reactions can be measured. Muonic tritium atomic beams with energy of the order of 1 eV have been produced via transfer and emission from solid hydrogen target containing small tritium concentrations. The μt energy distribution overlaps the predicted muonic molecular ($d\mu t$) formation resonances. Preliminary time of flight results are shown.

1. Introduction

Muon catalyzed fusion research has traditionally been carried out in gaseous or liquid hydrogen where a multiplicity of interactions obscures energy dependence measurements.

A target system has been developed at TRIUMF to permit the production of a low-energy "beam" of muonic atoms in vacuum. The emitted atoms can be observed in flight and subsequent reactions can be measured on an individual basis. The target allows observation of charged fusion fragments as well as neutrons. Fig. 1 illustrates the target, the different types of detectors and their positions. More details about the target and its specifications can be found in References [1, 2].

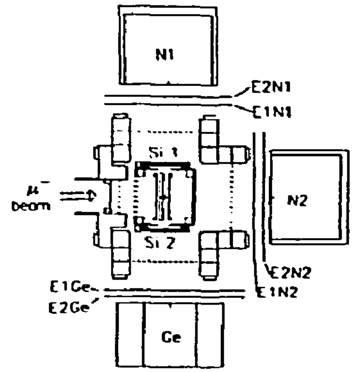

Figure 1: The arrangement of the target system and the detectors (top view).

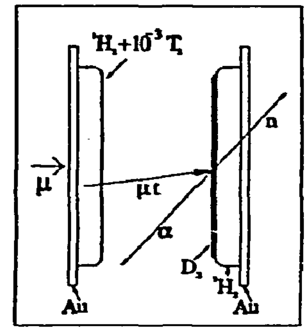

Figure 2: The physical layout of the hydrogen targets.

The target is made of two gold foils which are cooled to 3K. The distance between these foils is variable from 18mm to 40mm. A two sided gas diffusion mechanism allows the deposition of different types of hydrogen mixtures on the two foils. After a target deposition, the diffuser is removed. Fig. 2 shows a target configuration. Important features, considered during the design of the target system, were use of tritium and a limit on the number of materials in which a muon can stop.

When a muon is stopped in the hydrogen layer (mixture of hydrogen with $c_t = 10^{-3}$ of tritium) on the first gold foil, called the upstream foil, it forms a muonic hydrogen atom μp. This μp moves within the layer and disappears mainly by transfer to the tritium atom to form a muonic tritium atom μt. A full description of emission from a solid layer is described in Reference [3]. The μt atom loses energy by elastic scattering with hydrogen, but as the energy moderates to the range of a few eV, the cross section for scattering by a proton is drastically reduced because of the Ramsauer-Townsend (RT) mechanism [4, 5]. If the tritium concentration is not too high, the μt can travel a distance of the order of mm before the energy drops below the region where the Ramsauer-Townsend mechanism still occurs. If the adjacent region is vacuum, the μt will be emitted from the layer and will travel in vacuum until either it strikes another surface or the muon decays. The μt which reach the deuterium layer on the second gold foil, called the downstream foil, interact with the D_2. The main processes involved are $d\mu t$ molecular formation and scattering. When the $d\mu t$ molecule is formed, the fusion process occurs immediately and there is emission of an α and a neutron which may be detected (see Fig.1).

Calculations exist [6] for the rate as a function of energy in the interactions

$$\mu t + D_2 \rightarrow [(d\mu t)dee]^* \qquad (1)$$

The final state is a complex excited molecule analogous to hydrogen, where one of the "nuclei" is in fact a muonic molecular ion. It is the internal degrees of freedom of the complex molecule which lead to the resonance character of the reaction. It happens that the μt kinetic energies required to satisfy the resonance condition (Fig. 3) coincide remarkably well with the emission energy spectrum. Furthermore, the calculated rates are large enough to dominate the cross section for elastic scattering of μt by deuterons, the main mechanism for energy loss. This means that the resonant interaction may be observed by passing muonic tritium of the appropriate energy through a thin layer of D_2. The source of μt is the RT emitting hydrogen layer consisting of protium with one part per thousand tritium ($c_t = 10^{-3}$).

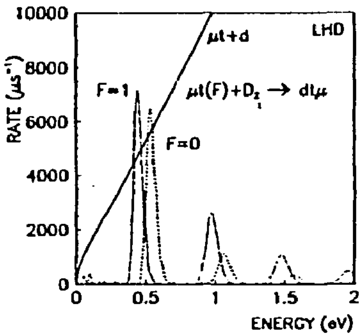

Figure 3: Predicted resonance structure of $\mu t + D_2$ at 3 K and density of liquid hydrogen, compared with rate of energy loss, for two hyperfine states of μt.

2. Techniques of measurements

The proposed experimental arrangement (see also [7]) is shown in Fig. 2. Muons, which form muonic protium and are transferred to tritons, exit the emitting hydrogen layer. A second target layer is placed close to the emitting layer, separated by approximately 20 mm of vacuum. The target layer consists of up to 1 mm of pure protium, covered by a thin overlayer of D_2. The thickness of the overlayer is chosen so that the probability of elastic energy loss by the incident μt is small. If the μt has the appropriate resonance energy, it can interact to form a muonic molecule in the overlayer. Fusion will follow immediately to give a measurable fusion product, either a neutron or an alpha particle. Otherwise, the μt atoms may pass through the vacuum to finally stop in the protium layer, where they give no signal which could be confused with a fusion event.

The general method of time of flight is well established. The energy of the projectile is deduced from the mass, the distance between two points, and the measured difference in time of detection at the points. In the case of the muonic atom experiments described here, the mass is that of a muonic atom (μt) formed via transfer of the muon from μp in a thin layer of solid hydrogen. The muonic atom is emitted from the hydrogen layer and can subsequently undergo the interactions of interest. One spatial point for the start of TOF is assumed to be in the plane of the layer, while the stop is at the point of a fusion interaction in the spatially separated thin layer (detected either via a α or a neutron). The time at which the muonic atom leaves the emitting layer is taken to be the arrival time of the muon in the experimental apparatus. Some uncertainty is introduced by this

estimation, and is described in the following section. The time of either muon decay, for attenuation measurements, or fusion product detection, for interaction measurements, signals the end of the time interval associated with the flight of the muonic atom.

The experimental setup (Fig. 1) is made to detect the α particle of 3.5 MeV with the two silicon detectors and the neutron of 14 MeV with the neutron detectors. These are produced during the deuterium-tritium fusion. The germanium detector is used to monitor the impurities of the different hydrogen mixtures and to observe the X-rays coming from transfer from μt to other materials in the target system. This study of transfer of μ^- is interesting [8] but represents a significant loss for the fusion channel.

3. Results

One of the first measurements with the improved design was to prove that the emission of a muonic tritium atom beam was possible. The results are comparable to that for muonic deuterium.

The next measurement performed was to see the alpha particle and the neutron which are emitted after the deuterium-tritium fusion. The setup for this measurement was an emission target (hydrogen with $c_t = 10^{-3}$) on the upstream foil with a thin layer of D_2 on top of it. Most of the μt which are emitted from the first layer will be stopped in this deuterium layer to form $d\mu t$ molecules and fusion will occur. All these events will take place shortly after the entrance of the muon in the target system. Most alpha particles and neutrons appear promptly with respect to the muon start signal.

The measurement of time of flight was then performed. The energy distribution of the fusion events is very similar to the previous measurement, however the time distribution is totally different. The time distribution of fusion events can be obtained by subtracting the time distribution of background, determined from another measurement where the downstream foil is not covered by deuterium. Fig. 4 show the most recent results obtain at TRIUMF. The background subtraction has been made very carefully and the rates are normalized to the number of muons which are stopped in the emission layer. This time of flight distribution shows events at $t > 3$ μs, especially with a thin downstream D_2 layer, which are due to direct resonant molecular formation. For the thicker D_2 layer, the time distribution is dominated by an indirect mechanism whereby the μt scatters in the layer before molecular formation, so that the time-of-flight is not indicative of the real resonance energy structure; even in the thinner layer, this is an unavoidable background.

To determine reliable values, or even to test for consistency with published calculations, a comparison with detailed Monte Carlo calculations is clearly essential. The computer program [9] which has been used includes the effects of transfer, molecular formation, scattering and emission. The results are show in Fig. 5. The normalization of the Monte Carlo simulation and the measurement are the same. One observes a similar reduction, in both results which is located around 3 μs. The main discrepancy is the unexpected difference of the rates above 3 μs; the Monte Carlo results are clearly larger than the experimental results. These preliminary results show some very interesting features which need to be studied in more detail.

4. Conclusions

The emission of muonic tritium from solid hydrogen is as well established as the one of deuterium. The time of flight technique coupled with a source of energetic muonic hydrogen isotopes offers opportunities for important measurements of muon catalyzed fusion processes. The measurement of time of flight of μt show evidence of events which are due to direct resonant molecular formation. More comparisons with Monte Carlo simulations must be done in order that the predictions of the theory can be tested with precision.

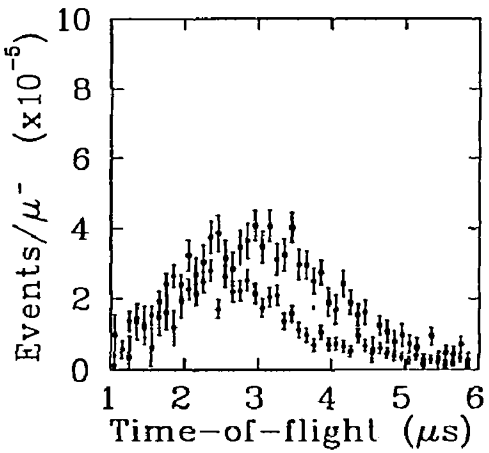

Figure 4: Si α time distribution for fusion in $21\mu g\ cm^{-2}$ D_2 (about one interaction length) (*black squares*) and *for a thicker* D_2 layer (*open circles*), *after background subtraction*. For better comparison, the intensity of the thicker D_2 layer has been divided by 10.

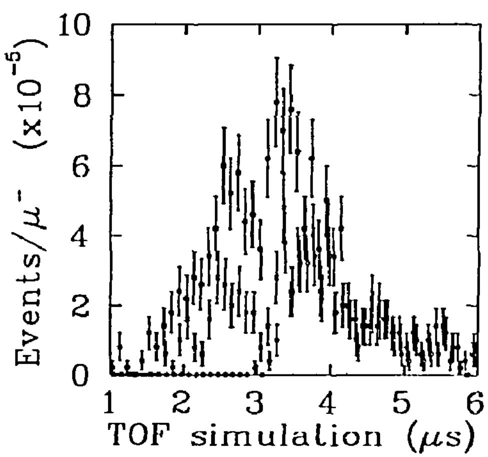

Figure 5: Monte Carlo simulation of fusion time distribution in $21\mu g\ cm^{-2}$ D_2 (black squares); contributions are indicated for direct (*i.e.*, *without previous energy loss collisions*) *formation in* all resonances (cross), and for only the main (0.35 eV $< E < 0.65$ eV) resonances (open circles).

Acknowledgements

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