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Time of flight spectroscopy with muonic hydrogen

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Abstract. Time of flight techniques coupled with muonic deuterium and tritium atoms in vacuum can be used to measure parameters important in the understanding of muon catalyzed fusion interactions. Muonic deuterium atomic beams with energy of order 1 eV have been produced via transfer and emission from solid hydrogen containing small deuterium concentrations. Measurements of energy loss in pure deuterium are presented which test calculations of $\sigma_{\mu d+D}$. Muonic tritium beams should be produced in a similar way, with an energy distribution which overlaps the predicted muonic molecular (dμt) formation resonances. The existence of resonances is crucial for high cycling rates in muon catalyzed fusion, but direct experimental verification of strengths and energies is not yet possible by other means. Results of simulations demonstrate how the resonance structure might be confirmed.

1. Introduction

The typical energy scale for many important interactions of muonic hydrogen atoms with hydrogen isotopes is electron volts or lower. It is necessary to understand processes

μd can travel for a distance of the order of 1 mm before the energy drops below ~ 0.1 eV and the cross section is no longer within the RT region. The mean time for transfer depends on the deuterium concentration[5,6], and is of the order of 100 ns for c_d of order 10^{-3}. At lower concentrations, the transfer probability is lower, while at higher concentrations the deuterium will reduce the distance which the muonic atom travels before thermalization[7]. If the muonic atom reaches the surface of the solid hydrogen layer during its travel, it will leave the layer. If the adjacent region is vacuum, the muonic atom will travel unimpeded until either it strikes another surface or the muon decays. Because the RT mechanism also exists for muonic tritium (μt) in protium, μt atomic beams should also be possible.

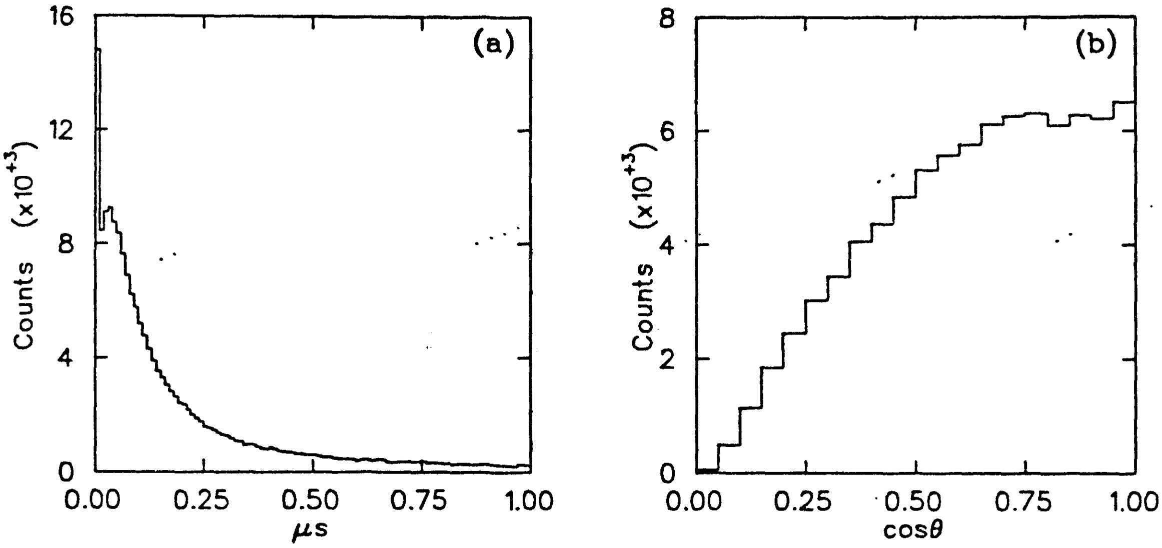

Figure 1: Distributions of (a)time of emission after muon entry, and (b) cosine of angle with respect to perpendicular, for muonic atom production from solid layer

Fig. 1(a) shows the distribution of emission times for a hydrogen layer, calculated via a Monte Carlo using measured transfer rates and realistic particle transport processes. The imperfect correlation between the time at which a muon is detected entering the target and the time at which the energetic muonic atom is actually emitted places a limitation upon the time of flight method. Fig. 1(b) shows the distribution of cosines of the angle of emission with respect to the perpendicular of the layer, which also limits the precision of TOF measurements; normally one measures only the perpendicular distance travelled, whereas the real distance depends inversely on the cosine. In what follows, the "energy" refers in fact to *longitudinal* energy, *i.e.*, corresponding to the velocity component *perpendicular* to the surface of the emitting layer.

The speed of a 1 eV muonic atom is 0.95 cm μs^{-1} for μd and 0.79 cm μs^{-1} for μt. The muon lifetime thus limits the path length for muonic atoms of this energy to a few cm. At least two types of measurement are envisaged, and are described below.

3. Attenuation measurements

The first type of measurement uses an attenuation technique. The effects of an interaction in a target layer located on the surface of the emitting layer change the energy

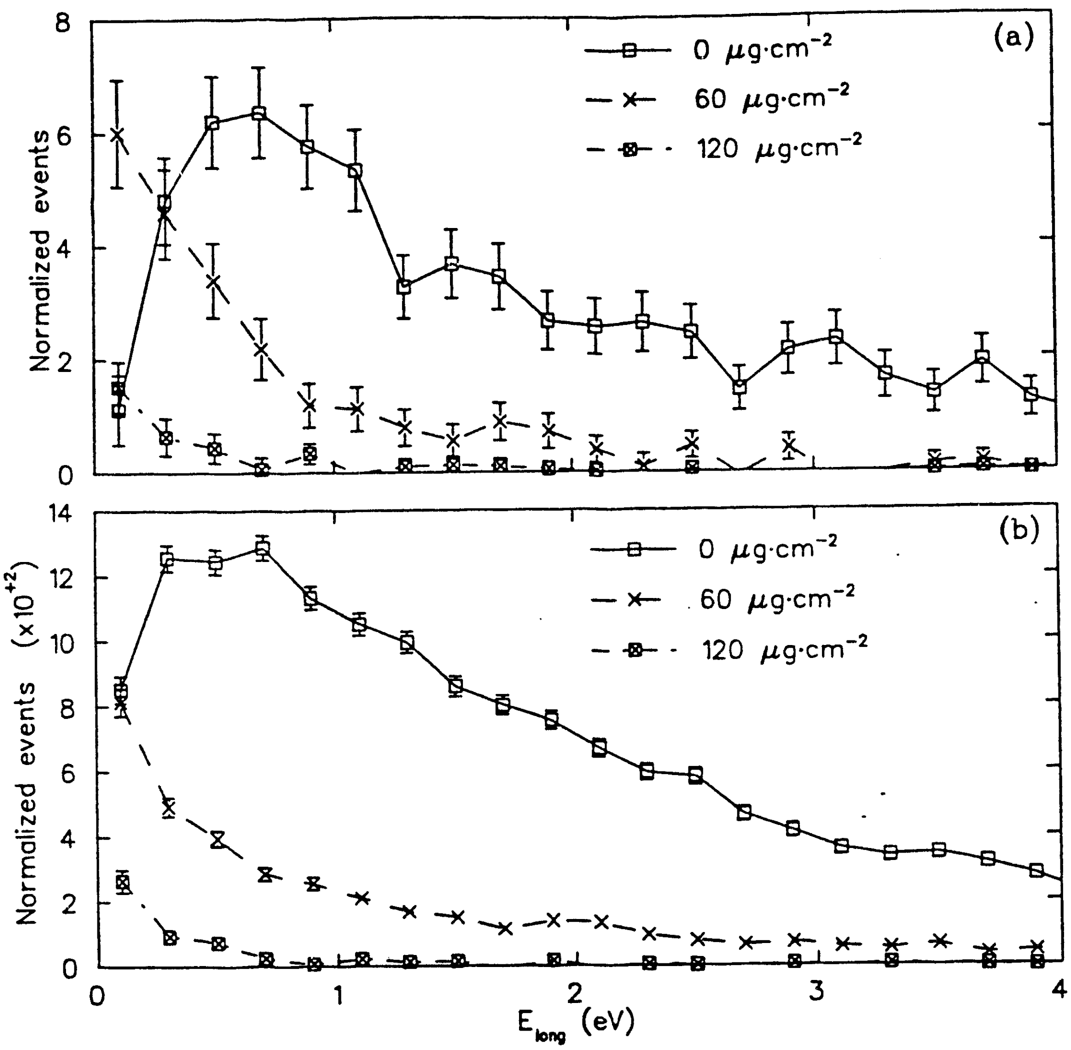

Figure 2: Distributions of longitudinal energy for different thicknesses of pure D_2 target layers, (a) measured, and (b) calculated via Monte Carlo.

molecular formation process is detectable while the mean energy loss via scattering is small.

The expected time distribution for fusion products, either neutrons or α particles, is shown in Fig. 4. The simulation assumes a separation of emitting and target layers of 15 mm, realistic transfer time to form μt, an emission angle following a cosine distribution similar to that shown in Fig. 1, and the theoretical resonant structure[1]. Backgrounds are not shown, but are not expected to dominate either for neutrons or α particles in the time region of interest. The effect of limiting the emission angle by transmission through an array of hexagonal collimating holes with dimension 3.1 mm and depth 5 mm is shown in Fig. 4(b). The emission angle distribution clearly precludes any precise measurement unless it is restricted by collimation. For a collimated beam, the corresponding energy resolution is less than 0.2 eV (full width half maximum) for the strongest resonance of Fig. 3 at approximately 0.3 eV.

5. Summary

The time of flight technique coupled with a source of energetic muonic hydrogen isotopes offers opportunities for important measurements of muon catalyzed fusion processes. Two quite different experiments have been considered so far, one based on attenuation during passage of a muonic hydrogen beam through a target layer, and another based on its interaction in a spatially separate target layer. The main limitation is that the energy regime is restricted to approximately 0.1-10 eV because of the mechanism of production and detection. It is absolutely essential to understand the processes in detail, via computer simulation, in order that the predictions of the theory on which the simulations depend can be tested with precision.

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References

[1] M.P. Faifman and L.I. Ponomarev, Phys. Lett. B **265**, 201 (1991).

[2] B.M. Forster *et al.*, in *Proceedings of the 5th International Conference on Muon Spin Rotation, Relaxation, and Resonance (μSR 90), Oxford, 1990,* edited by S.F.J. Cox, G.H. Eaton, D. Herlach, and V.P. Koptev, Hyperfine Interactions **65**, 1007 (1990); G.M. Marshall *et al.*, in *Proceedings of an International Symposium on Muon Catalyzed Fusion μCF-89, Oxford, 1989*, edited by J.D. Davies, (Rutherford Appleton Laboratory Report RAL-90-022).

[3] C. Chiccoli, V.I. Korobov, V.S. Melezhik, P. Pasini, L.I. Ponomarev, and J. Wozniak, "Atlas of the Cross Sections of Mesic Atom Processes", Muon Catalyzed Fusion **7**, 87 (1992); A. Adamczak, C. Chiccoli, V.I. Korobov, V.S. Melezhik, P. Pasini, L.I. Ponomarev, and J. Wozniak, Phys. Lett. B **285**, 319 (1992).

[4] James S. Cohen and Michael C. Struensee, Phys. Rev. A **43**, 3460 (1991).

[5] R. Jacot-Guillarmod *et al.*, in *Proceedings of the International Workshop on Muon Catalyzed Fusion*, μCF-92, to be published in Muon Catalyzed Fusion.

[6] A. Bertin, M. Bruno, A. Vitale, A. Placci, and E. Zavattini, Phys. Rev. A **7**, 462 (1973).

[7] G.M. Marshall *et al.*, in *Proceedings of the Workshop on the Future of Muon Physics, Heidelberg, 1991*, Z. Phys. C – Particles and Fields **56**, S44 (1992).

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