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EXPERIMENTS WITH ENERGETIC μd AND μt EMITTED FROM SOLID HYDROGEN

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A set of experiments is reviewed which makes use of the emission of muonic deuterium from the surface of a layer of solid hydrogen. The behaviour of muons in a solid target system has been studied via detection of muon decay electrons, muonic x-rays, and fusion products (neutrons and charged particles). The emission of muonic deuterium is understood to result from the Ramsauer-Townsend scattering minimum. The energy distribution of the emitted atoms ranges from tenths of eV to about 10 eV, and can be controlled to some extent. A proposal

is described to use muonic tritium emission to measure the energy dependence of muonic molecular formation.

1. Introduction

Muon catalyzed fusion research has evolved substantially. The experiments of past years have formed a solid basis, and as in the case of most interesting research, more questions arise as progress is made. Theoretical models have been refined and improved so that testing their predictions is beyond the capability of existing methods of measurement. Meanwhile, issues of safety and environmental responsibility set limits for the parameters of experiments which try to meet new challenges with tritium targets under extreme conditions. It is not surprising, then, that new and comparatively unconventional approaches are being considered in μCF. One such approach is the use of triple mixtures of hydrogen isotopes, which exposes very important kinetic effects. Another example is the application of energetic muonic hydrogen atoms in vacuum, in which a solid layer of hydrogen containing a small concentration of deuterium or tritium is used as a source.

It has already been shown that one can prepare μd and likely μt atoms in a neutral "beam" in vacuum in the 1s atomic state with an energy of order 1 eV. Recently we have observed dd fusion protons from a pure solid deuterium layer formed on the surface of a hydrogen target containing one part per thousand deuterium. The data indicate that the fusion results from emission of muonic deuterium after formation by transfer in the hydrogen layer. A new target system has been constructed [1] which allows the preparation of two parallel hydrogen layers separated by a distance of up to 40 mm. One layer can be used as an emitter of μd or μt, while the other is used as a target layer for the muonic atomic beam. For example, energetic μt atoms can strike a thin target layer containing deuterium. It should be possible to use the time of flight between the emitter and the target to characterize the energy at which molecular formation is resonant. Recent theoretical work has emphasized the energy dependence which can be extracted using a two layer system.[2]

The important aspects of the emission mechanism for μd are as follows. If a muon slows in protium containing a small deuterium concentration, it will normally initially form muonic protium, μp. Transfer of the muon from the proton to a deuteron is possible because the increase in reduced mass leads to a slightly larger binding energy. This also leads to an appreciable kinetic energy (about 45 eV) of the μd after transfer. The average time for transfer depends on the deuterium concentration,[3,4] and is of the order of 100 ns for c_d of order 10^{-3}. The μd 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.[5,6] If the deuterium concentration is not too high, μd can travel for a distance of the order of 1 mm before losing so much energy that the cross section is no longer within the RT region. The muonic atom then thermalizes without further macroscopic displacement.

If the muonic atom reaches the surface of a solid hydrogen layer during its travel, it will be emitted from the layer. If the adjacent region is vacuum, the muonic atom will travel unimpeded until either it reaches another material or the muon decays. Because the RT mechanism exists for muonic tritium (μt) in protium, the same situation arises. Note that these are the only isotopic mixtures where it is expected; for example, there is no analogous RT minimum for muonic tritium in deuterium.

Experiments have been performed at TRIUMF over the past several years with the aim of understanding the factors which control emission of muonic deuterium from a solid layer. Extension of the program to include muonic tritium is anticipated in the near future.

2. Techniques of measurement

Several detection systems have been used to understand the emitting targets in a series of experiments with hydrogen containing deuterium. The feasibility of measurements important in μCF research has also been demonstrated by identifying dd fusion products. Details of the experimental arrangement are given elsewhere in this volume.[1]

The emission of muonic deuterium can be observed by reconstructing the path of muon decay electrons in order to infer the position of decay. A more complete description can be found in the literature,[7] but the important points are as follows. A system of three wire chambers measures spatial coordinates of the electron, and scintillation counters and a sodium iodide crystal determine the time and energy of the electron respectively. The energy measurement is used simply to reject lower energy background and in some cases to improve position resolution by choosing only electrons with energy above a certain threshold; a lower energy decay electron undergoes a larger average scattering angle in material in its path. The time measurement is more important, because muons stopping in heavier elements (such as Au) which make up the cryostat are quickly absorbed. The major source of electrons later than 0.5 μs after the muon arrival time is therefore from muon decay in hydrogen. In addition, the correlation of time and position is a measure of the component of velocity perpendicular to the solid hydrogen layer. The position of decay is estimated by extrapolation of the three electron coordinates to a plane containing the beam axis.

Complementary information has been obtained from muonic x-rays measured by a high resolution germanium detector. The eventual fate of muons is clarified by the observation of muonic radiative transitions either after direct capture or after transfer from muonic hydrogen to heavier atoms. The two processes can be distinguished both by the different time dependences and by the characteristic cascade relative intensities. Muonic x-ray information has been used to monitor possible contamination of the targets and to verify the muon stopping distribution. It has also proved possible to extract reasonably precise estimates of the rates for transfer from

protium to deuterium and for muonic molecular formation in protium, as described more completely in another contribution to this volume.[3]

Neutron detectors form yet another component of the apparatus. During tests and background studies, the solid target provided an opportunity to measure for the first time the characteristics of muon catalyzed dd fusion at a temperature below 10K. A comparatively thick (several mm) layer of solid pure D_2 at 3K was used; of course, no emission was expected, and the muons remained in the deuterium layer. Careful measurements by other groups in the liquid and gas phases at higher temperatures have existed for some time, and have been well understood in terms of hyperfine effects and muon molecular formation from thermalized μd.[8,9] On that basis, no appreciable resonance formation of dμd was expected. However, preliminary results are consistent with an effective molecular formation rate from the $F = 3/2$ hyperfine state of $\tilde{\lambda}_{3/2} = 2.88 \pm 0.35\ \mu s^{-1}$ and an effective hyperfine conversion rate of $\tilde{\lambda}_{3/2 \to 1/2} = 33.3 \pm 2.4\ \mu s^{-1}$, normalized to liquid hydrogen density. The resonance behaviour is therefore similar to that observed in warmer targets; a comparison is made elsewhere in this volume.[10] It is likely that the solid phase of the target modifies the processes substantially, and that the analysis which has been so successful at higher temperatures is no longer adequate.

While the interpretation of the solid D_2 result is not yet clear, the experiments are being repeated with a modified arrangement. A silicon charged particle detector has been added to detect the mirror branch of the dd fusion reaction which results in a proton and a triton. By observing the proton at the same time as the neutron from the n-^{3}He branch, the branching ratio for fusion from the molecular state following resonant formation can be compared to the one corresponding to non-resonant formation. The use of silicon detectors will also contribute to future experiments, such as the one outlined in the following section.

3. A proposed experiment with tritium

It has been proven that the RT process in a solid layer can be used to create energetic muonic deuterium atoms in vacuum. The typical energy of the atoms is determined by the shape of the Ramsauer-Townsend minimum in the cross section. In the case of muonic deuterium, the distribution of the longitudinal energy (*i.e.*, the energy corresponding to the longitudinal component of velocity) has a most probable value of about 1 eV. Calculations of the RT minimum for muonic tritium in protium show a similar energy dependence, so we expect that muonic tritium will have an energy distribution similar to that for muonic deuterium.

Recent calculations exist[2] for the rate as a function of energy in the interactions

$$\mu t + DX \rightarrow [(d\mu t)xee] \qquad (1)$$

where x is p, d, or t and X is the corresponding atomic form. DX is the molecular state of deuterium with X, and e is an atomic electron. The final state is a complex 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 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 HD or D_2. The source of μt is the RT emitting hydrogen layer, protium with one part per thousand tritium ($c_t = 10^{-3}$).

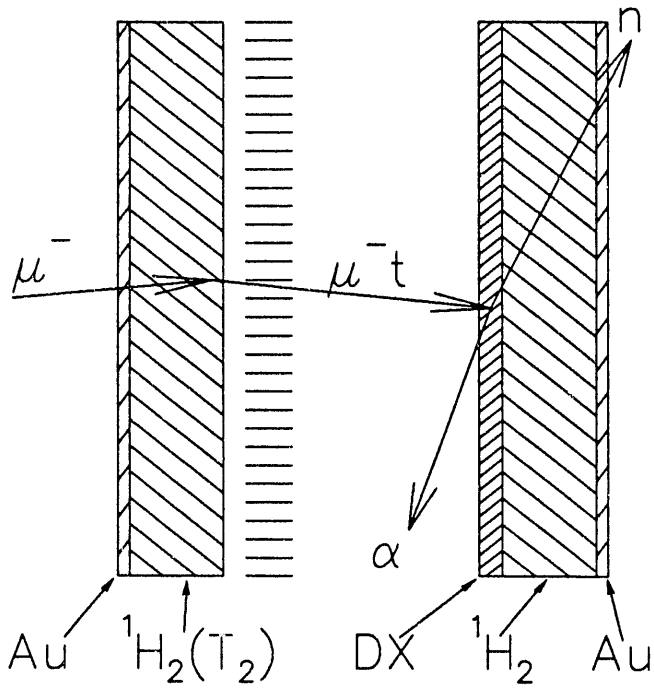

Figure 1: Proposed arrangement of two solid hydrogen layers for measuring the energy dependence of the resonant muon molecular formation rate (not to scale)

The proposed arrangement of hydrogen layers is shown in Fig. 1. Muons which form muonic protium and are transferred to tritons exit the emitting hydrogen layer. A second target layer is 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(or HD, depending on the resonance structure we wish to measure). The thickness of the overlayer is chosen so that the probability of energy loss by the incident μt via elastic processes is small. For a cross section of 5×10^{-19} cm^2, the interaction length is equivalent to 10 $\mu g \cdot cm^{-2}$, or 0.5 μm at $\phi = 1$. If the μt has the appropriate resonance energy, it can interact to form the 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 to finally stop in the protium layer, where no signal is expected which could be confused with a fusion event. For each individual μt which participates in the fusion interaction, the incident energy is determined by its time of flight between the emitting layer and the target layer. The time of emission is approximately the

time of muon arrival, as measured by a scintillation counter in the incident muon beam, because the transfer process is quite fast at the chosen tritium concentration. The time of arrival at the target layer is given by the time of detection of the fusion product, because fusion follows within nanoseconds of muon molecular formation. By far the greatest limitation on the precision of the time of flight energy determination is the unknown angle of emission of the μt. A collimating device is used in the vacuum drift space to limit the angles to a range close to perpendicular with respect to the emitting surface.

4. First results with an improved target system

In order to proceed with the measurement described in the previous section, we have constructed a new cryogenic target system. It incorporates improvements over the initial system defined by the demands of the new experiment plus several years experience with solid hydrogen layer targets.

The features which were considered important for the new system are as follows. Two cold surfaces should be adjacent to each other, with spacing between them variable from less than 10 mm to 40 mm. It must be possible to form solid layers on each surface independently, with no significant cross-contamination. The system should be capable of containing small amounts (up to 10 curies) of tritium safely. Materials in which the muon beam might stop should be restricted to the hydrogen layers and heavy, pure cryostat material (Au or Ag, but not both), in order to eliminate spurious muonic x-rays and longer lived capture neutrons. The thickness of material through which the muon beam must pass before stopping in hydrogen should be minimized, in order that the beam momentum (and therefore the momentum spread) is as small as possible. Control of the temperature should be reliable at about 3K with reasonable liquid helium consumption. Versatility is very important, so that different detector configurations, angular collimators, and target arrangements can be considered. A more complete discussion of target features is found in ref. [1].

One of the first measurements with the improved design was to prove that two dissimilar target layers could be formed without significant cross-contamination. The principle of formation of the solid layer is that hydrogen molecules stick almost completely at first contact with a 3K surface. If they do not, it is possible that some molecules may bounce around the diffuser and stick to the other cold surface, which would make the complicated layer structure of the tritium experiment impossible. To test whether this might be a problem, an emitting layer was first deposited on one foil. The yield of μd in the vacuum space between the two foils was measured by decay electron imaging. Then a substantial layer of pure D_2 was deposited on the opposite foil, and the measurement was repeated. If a significant amount of D_2 contaminated the surface of the first foil, μd arriving at the surface would lose energy by scattering on deuterium and the yield would be drastically reduced. No significant reduction was observed, establishing that less than 0.5% of the deuterium

contaminated the opposite surface.

The intensity reduction of μd during passage through a thin overlayer of D_2 is due essentially to scattering. At 1 eV the μd scattering cross section by a deuteron is typically of order 10^{-19} cm^2, which is several orders of magnitude larger than that for scattering by protons in the RT minimum. The effect of a deuterium overlayer on both the intensity and the longitudinal energy E_l of the emitted atoms has been studied with the new target system. The longitudinal energy is derived from the time of flight before decay, assuming the mass of μd.

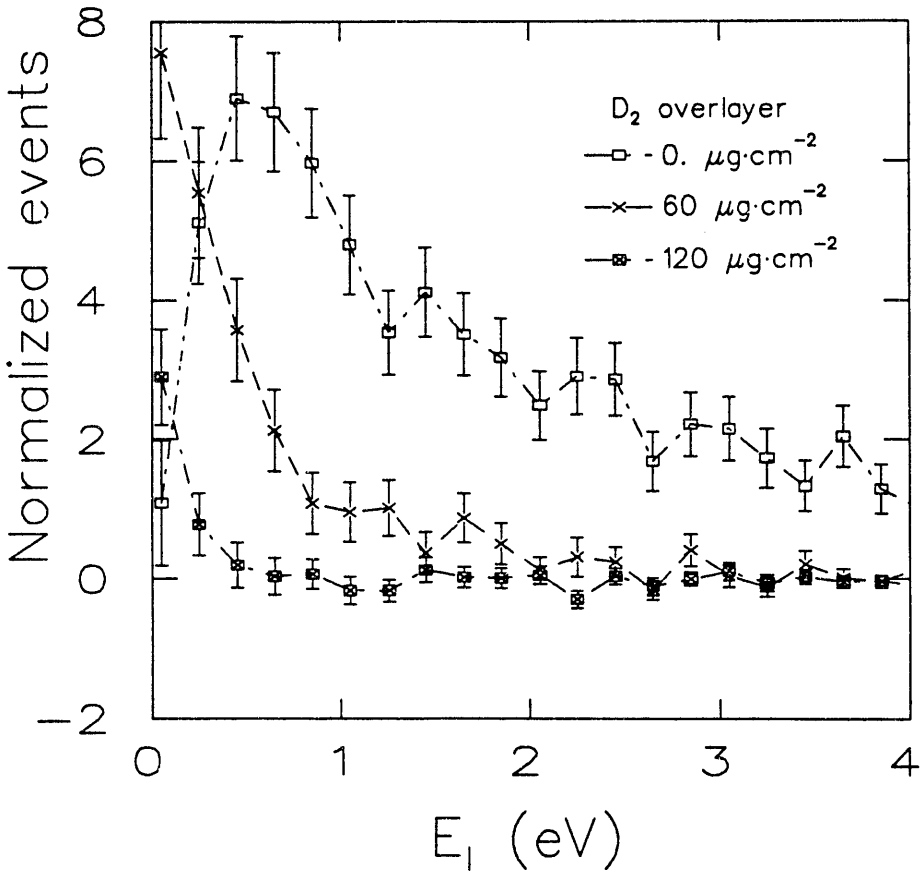

Figure 2: Longitudinal energy distributions for different D_2 overlayer thicknesses, for muonic deuterium which decays between 10 and 30 mm from the emitting surface

The intrinsic motivation for studying E_l is twofold. First, we can hope to extract from measurements the cross section as a function of energy for a range of μd kinetic energy around 1 eV. To determine reliable values, or even to test for consistency with published calculations,[11] a comparison with detailed monte carlo calculations is clearly essential. The computer program which is being developed includes the effects of transfer, molecular formation, scattering, and emission, all of which are necessary in this case. Second, it has become clear that the properties of the emitted μd can be controlled to some extent due to energy loss in the overlayer. Fig. 2 shows longitudinal energy distributions based on muons decaying between 10

and 30 mm from an emitting layer, for two overlayer thicknesses as well as for no overlayer. In all cases, the distributions have been normalized and a similar one from a pure protium layer has been subtracted. The reduction in intensity is obvious, but it is interesting to note the shift in the energy spectrum of the emitted μd. Keeping in mind that the strongest resonances in the reactions of (1) are in the range 0.2–0.6 eV, it may be advantageous to use an overlayer to adjust the spectrum of emitted energies. The first experiments with muonic tritium emission will show whether such control is practical.

The neutrons following dt fusion form a reasonably unambiguous signature for the determination of the time of flight of muonic tritium, in the arrangement of Fig. 1. This is especially true since the major contribution to the time-dependent background is from muon capture in heavy materials, which occurs before the time at which muonic tritium is expected to reach the target layer. Measurements of the neutron background confirm this. However, in the geometry imposed by the vacuum and cryogenic systems, the efficiency of counting neutrons is not as high as one might wish. To improve fusion detection efficiency, silicon charged particle detectors can be incorporated adjacent to the hydrogen layers.[1] A 4 MeV α is an unambiguous signature of dt fusion. Tests of several detectors have shown that they will operate reasonably well within the cryostat, without serious negative effects from hydrogen gas absorption, low temperature, or muon decay radiation background.

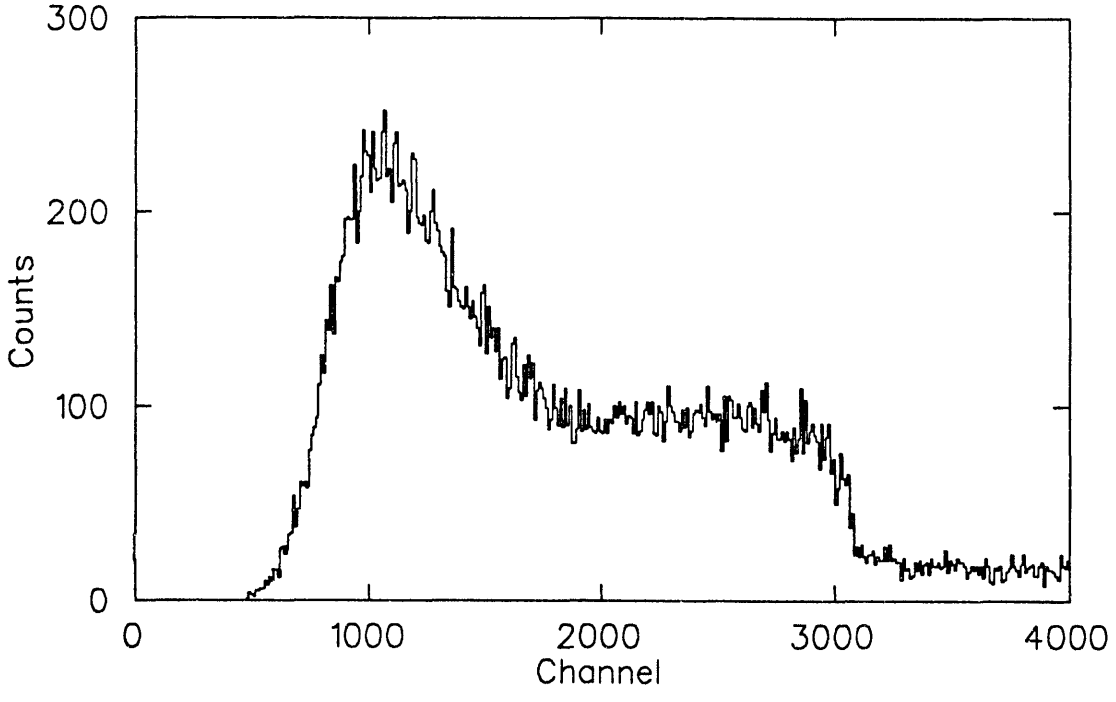

Figure 3: Energy in a silicon detector for a deuterium target. The energy calibration is very close to 1 keV per channel

Experiments have been performed to detect the 3 MeV protons from dd fusion. Both energy and time determination are important. In Fig. 3, the energy from

a deuterium target shows an edge at 3 MeV, extending down and into a background structure at lower energy. It may be contrasted with the sharp 3 MeV structure shown elsewhere in this volume,[1] in which the target consisted of a thin D_2 overlayer on a hydrogen ($c_d = 10^{-3}$) emitting target. The difference is that the thicker target causes energy loss by the outgoing protons for fusion events that happen within the layer, as opposed to within the surface overlayer.

5. Conclusions

The emission of muonic deuterium from solid hydrogen is well established and understood semi-quantitatively, based on accepted cross sections and transfer rates. However, detailed comparisons with monte carlo calculations will make more precise estimates possible. The properties of muonic tritium emitted from a solid layer may be very similar, but it is essential to make measurements in order to examine any differences. Several applications exist for hot muonic hydrogen atoms in vacuum. A few of the possibilities are being pursued, but it is probable that others exist which have not yet been considered.

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