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TECHNICAL PROGRESS REPORT

EXOTIC ATOMS

By

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DISCLAIMER

ABSTRACT

A variety of hydrogen isotopic mixtures form solid targets to produce muonic hydrogen isotope atoms. The method relies on muon capture by a proton and transfer of the muon from the proton to a deuteron or a triton. The resulting muonic deuterium or muonic tritium will not immediately thermalize because of the very low elastic cross sections of the Ramsauer-Townsend effect, and are emitted from the surface of the layer and escape into a vacuum region. A second solid hydrogen isotopic target is produced downstream on which the muonic hydrogen atom can react and the time of flight measured.

INTRODUCTION

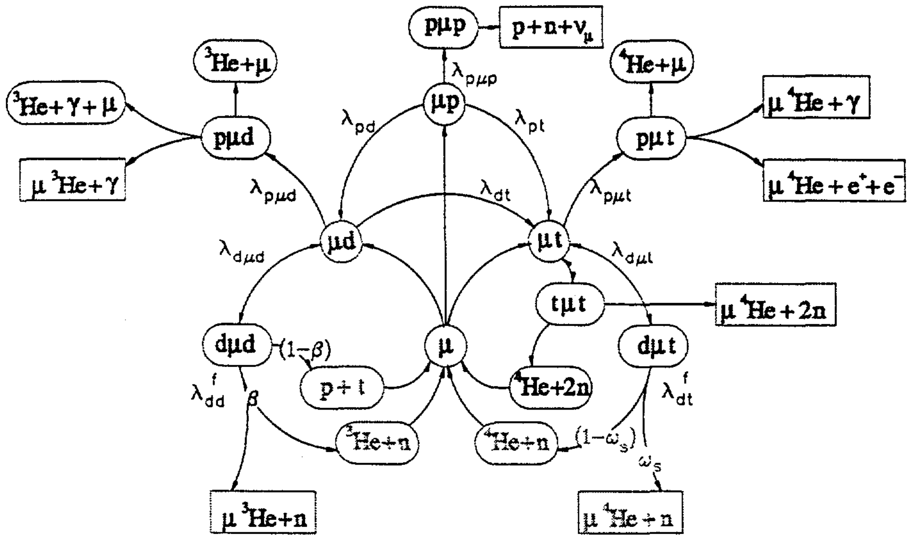
Measurements which detect decay electrons, muonic x-rays, and fusion products have been used to study the processes of energy dependence of transfer, production rates, and muon molecular formation. The processes include muon catalyzed fusion of muonic tritium with deuterium which is the most possible candidate for energy production. Other experiments are being developed including one to measure the energy dependence of the Ramsauer-Townsend cross section with tritium where it has not been measured and one to measure the alpha sticking probability for the muon. Our ultimate interests are the nuclear physics reaction rates and to use the muonic hydrogen isotopes in vacuum for energy level measurements.

The time at TRIUMF during my sabbatical leave was enjoyable and productive and I have worked closely on all aspects of the experiments, especially the data analysis and preparation of reports. These are parts of the experiment easily transported to the University of Wyoming campus. This year involved much reading and correcting manuscripts as one can determine by a glance at the publications listed at the end of the report. The diagram on the next page is taken from a report submitted to the subatomic physics planning committee at TRIUMF. The diagram shows the range of topics that will be discussed in the next section. The next beam time at TRIUMF will be January 31, 1996 to February 21, 1996.

MEASUREMENTS

Time of Flight Measurement of Resonant Molecular Formation in dt Fusion

The energy dependence of the rate for muon catalyzed dt



Simplified diagram of muonic processes in the TRIUMF solid hydrogen/deuterium/tritium target showing *observable states* and some parameters which *have been measured* or *will be measured.*

$\lambda_{\mathrm{p}\mu\mathrm{p}} = (2.90\pm0.19)\cdot 10^6\ \mathrm{s}^{-1}$ and $\lambda_{\mathrm{pt}} = (5.96\pm0.26)\cdot 10^9\ \mathrm{s}^{-1}$
F. Mulhauser *et al.*, submitted to Phys. Rev. A

$\lambda_{\mathrm{p}\mu\mathrm{p}} = (3.56\pm0.55)\cdot 10^6\ \mathrm{s}^{-1}$ and $\lambda_{\mathrm{pd}} = (1.75\pm0.19)\cdot 10^{10}\ \mathrm{s}^{-1}$
R. Jacot-Guillarmod *et al.*, submitted to Hyp. Int.

$\lambda^{3/2}_{\mathrm{d}\mu\mathrm{d}} = (2.71\pm0.39)\cdot 10^6\ \mathrm{s}^{-1}$, for $F_{\mu\mathrm{d}} = 3/2$
$\lambda^{1/2}_{\mathrm{d}\mu\mathrm{d}} = (5.2\pm1.1)\cdot 10^4\ \mathrm{s}^{-1}$, for $F_{\mu\mathrm{d}} = 1/2$
$\lambda_{3/2\rightarrow1/2} = (34.2\pm0.9)\cdot 10^6\ \mathrm{s}^{-1}$, for the hyperfine transition rate
P.E. Knowles *et al.*, Ph.D thesis (U Vic) in preparation
P.E. Knowles, submitted to Hyp. Int.

$\lambda_{\mathrm{d}\mu\mathrm{t}}(E)$ with D_2, first measurement via TOF
M.C. Fujiwara, Ph.D thesis (UBC) in preparation
G.M. Marshall *et al.*, submitted to Hyp. Int.

$\lambda_{\mathrm{d}\mu\mathrm{t}}(E)$ with HD, beam allocated
T.A. Porcelli, Ph.D thesis (U Vic) in preparation

ω_S
M.C. Fujiwara *et al.*, proposal in preparation
M.C. Fujiwara, M.A.Sc. thesis (UBC)
M.C. Fujiwara *et al.*, submitted to Hyp. Int.

fusion is being studied by a time of flight technique. Calculations exist for the rate as a function of energy in the interactions

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

where x is p, d, or t and X is the corresponding atomic form, P, D, or T. The final state is a complex molecule analogous to hydrogen, where one of the "nuclei" is in fact a muonic molecule itself. 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 a few parts per thousand tritium. The experimental apparatus allows us the necessary flexibility to produce all desired targets in the vacuum region.

The main goal of the analyses has been to determine the energy dependence and rate of μdt resonant formation. The principle is to use the time of flight of a μt atom emitted from an upstream emitting layer, which subsequently forms μdt in a D_2 layer and immediately fusions. The target and detector geometry were optimized for this measurement, and several other measurements and test measurements were possible.

The separation of the two gold foils upstream and downstream was reduced from 39 mm to 18 mm, so lower energy muonic atoms would survive the passage. Si detectors were mounted on each side of the cryostat cold shield, viewing the region between the foils and (at a large average angle) the foil surfaces. The detectors were collimated with a vertical slot of about 14 mm, centered on the gap between the foils, to reduce tangential fusion product detection. Neutron detectors were mounted to the beam left and downstream, while the Ge detector was at the right of the beam direction. All three systems included a pair of scintillators to act as charged particle vetos and post-fusion delayed electron identifiers. No wire chambers were used.

Data was obtained with various target layers on the upstream cold foil. Thicker layers of deuterium were added to downstream to determine the total μt flux at the downstream layer. Several concentrations of tritium allowed variations for emission and pt transfer rate determination.

One unexpected feature of the data so far is that no strong signal was seen from dd fusion from the residual muon after dt fusion in the deuterium overlayers. This is still not resolved, but a run was done with a deuterium overlayer on the μd emitting US layer, to prove that the Si detectors could see the dd fusion protons. It worked as it should. Where are the residual dd fusion protons following dt fusion? It could be that the muons have a much higher energy than expected. Or, perhaps the muons do not lose energy in the solid layer according to calculations. Something is not understood.

Formation of the deuterium-tritium muonic molecular ion (dtμ) is a key process necessary to sustain high cycling rates in muon catalyzed dt fusion. The formation rate is typically inferred from fusion neutron time distributions in gas or liquid targets, but the complicated sequence of interactions in the fusion cycle frustrates any measurement of its dependence on energy. Because of resonance effects, the energy dependence is dramatic and important for the interpretation of experimental results as well as the design of applications. Without resonant formation, observed yields of more than 100 fusions per muon are inconceivable.

Previous results at TRIUMF have shown that it is possible to create dμ atoms in a neutral "beam" in vacuum in the 1s atomic state with energy approximately in the range 0.1 - 10 eV. The similarity in theoretical cross sections for elastic scattering of dμ and tμ, where the Ramsauer-Townsend mechanism leads to low cross sections and long interaction distances for energies around 1 eV, showed that tμ could be created in vacuum with the correct properties for a unique measurement. Motivated by the possibility of a direct measurement of the resonance structure, a tritium-compatible cryogenic solid hydrogen target system was constructed and commissioned in December 1993. A total of 9,600 GBq (260 Ci) of tritium from Ontario Hydro was brought to TRIUMF. About 500 GBq (13 Ci) were used in preparation of experimental targets consisting of a mixture of protium with a few parts per thousand tritium concentration, frozen in a layer to a cold gold substrate. No measurable tritium release was observed in either the roof stack exhaust connected to the outer enclosure of the target and gas handling systems, or in the room air monitor, although both were sensitive to tiny amounts of airborne radioactivity due to normal high current operations in BL1A. The tritium was stored before and after the experiment in the form of a stable solid hydride.

The tμ atoms emitted via the Ramsauer-Townsend mechanism from a solid protium-tritium layer can be caused to collide with a pure D2 layer. By observation of the fusion products, the subprocesses described by the dtμ rate can be isolated. After formation of the molecular ion, dt fusion occurs very quickly with rate 10^{+12} s^{-1}, leading typically to an alpha particle of 3.5 MeV and a neutron of 14 MeV, both of which can be detected. The alpha is particularly useful as a signal of fusion, because the signal is unambiguous in a silicon detector, the background is low, and the efficiency is reasonable.

The time distribution of fusion events can be obtained by subtracting the time distribution of background, determined from events with energy displaced from the prominent alpha energy peak, from the raw time distribution of the peak itself. The events occur within about 0.4 micro s of the muon's arrival, showing the time distribution with which muonic atoms are emitted from the layer.

Another set of data was taken in which a D2 layer was deposited on a parallel surface 39 mm from the emitting layer, so that the time of fusion product detection represents the additional time of flight of muonic tritium from one layer to the other. The distance was reduced to facilitate some very interesting measurements with $t\mu$ down to about 0.5 eV, where resonance effects in muon molecular formation were quite distinct.

Reliable Target Thickness Measurements

The target system for solid hydrogen thin films developed at TRIUMF is proving to be a powerful tool in muon catalyzed fusion research and an important necessity is to reliably know the target properties. Characterizing the thickness and uniformity of target films is essential in extracting physical parameters such as cross sections from experimental data. We measure the film thickness and uniformity using energy loss of alpha particles. A precision of a few percent is achieved which is limited by the knowledge of the stopping powers of solid hydrogen. The method now can be applied to other experiments where characterization of thin solid targets is required. The details of the technique and the results of the measurements in various targets were presented at the Dubna Conference.

Measurement of the Muon Transfer Rate from p to t in Solid Hydrogen Targets

The knowledge of muon transfer from protium to tritium is mostly theoretical and the values disagree. Using solid hydrogen-tritium targets with different tritium concentrations we have been able to obtain precise experimental results for the transfer rate to tritium and the ppmu molecular formation rate.

When muons are stopped in a solid hydrogen-tritium target muonic protium atoms $p\mu$ are formed and the muons are transferred to tritons to form muonic tritium atoms $t\mu$ or will form $pp\mu$ molecules. The emission of $t\mu$ atoms into a deuterium layer produces $dt\mu$ molecules where dt fusion takes place, emitting neutrons and alpha particles. When the deuterium layer is downstream, the time spectra are used to determine the transfer rates and the molecule formation rate.

Muon Molecular Formation and Transfer Rate in Solid Hydrogen-Deuterium Mixtures

In an experiment to study muon catalyzed fusion and associated atomic and molecular effects, negative muons were stopped in a solid hydrogen target contaminated with deuterium. Most of the pμ atoms disappeared by formation of ppμ molecules or muon transfer to a deuteron. The latter can drift almost freely through the hydrogen layer, due to the Ramsauer-Townsend effect, and may even leave the layer. If a thin neon layer is frozen atop the hydrogen, the exiting muonic atoms will very rapidly release their muon to a neon atom. The excited muonic neon atom will reach the ground state by emitting characteristic muonic rays. The analysis of the time structure of these x rays, especially those of the μNe(2-1) transition, are being used to determine the rates of the slower processes involved in the evolution of the dμ. This analysis has been performed with the help of Monte Carlo calculations, which simulate the kinetics of both pμ and dμ atoms in the hydrogen mixtures.

Muon Catalyzed Fusion in Deuterium at 3K

Muon catalyzed fusion has been studied in gaseous and liquid deuterium targets. The solid hydrogen layer target system has been used to study the fusion reactions rates in the solid phase at a target temperature of 3K. Both branches of the cycle were observed; neutrons by a liquid organic scintillator, and protons by a silicon detector located inside the target system. Information on the reaction rates, including the branching ratio, have been extracted from the measured spectra. Details on the experiment, analysis, and interpretation of results were presented.

FUTURE EXPERIMENT PLANNING

Further Resonance Formation Measurements

We are considering the choices of where to proceed. Current thinking includes doing a TOF measurement with HD. An equilibrated mixture of 10% D_2 and 90% H_2 would allow us to make a target relatively free from D_2, and the large H_2 fraction remaining would not be a severe restriction to a measurement on HD. It would be rewarding to get a Si detector working as the downstream target substrate, to increase our efficiency by a large factor. The problems we anticipate are making the Si work at 3K, and dealing with beam-related backgrounds which have given us a problem in a previous run with a detector on the diffuser mechanism. Two other plans are for further Ramsauer cross section measurements and for alpha sticking of the muon in td fusion.

Investigation of Muonic Hydrogen Isotopes Scattering

The knowledge of cross sections for scattering of $p\mu$, $d\mu$, and $t\mu$ on molecules of hydrogen isotopes is necessary not only for checking the algorithmic solution of the Coulomb three-body problem but also for a general and correct description of the kinetics of muonic and molecular processes in mixtures of hydrogen isotopes.

Although much theoretical research has been devoted to the calculation of these cross sections, less has been done to study the scattering experimentally. Discrepancies exist among the few experimental values and between experiments and theory. We plan to measure the scattering cross-section energy dependence of the reactions

$$\mu x + H_2 \quad -> \quad \mu x + H_2 \quad (x = d,t)$$

in the energy collision range from 0.1 to 45 eV using a multilayered target system.

Measuring Sticking and Stripping in Muon Catalyzed dt Fusion with Multilayer Solid Films

A test to search for mu-alphas resulting from sticking was conducted to guide future research. An H_2 layer can separate the energy of the alphas with and without attached muons by dE/dx. We propose a direct measurement of muon sticking to helium in muon catalyzed dt fusion at a high density. The charged fusion products, alpha and mu-alpha are directly detected by using the solid hydrogen target system developed at TRIUMF. The multilayer nature of the thin film targets allows us to isolate the processes in μCF. A layer of protium with a small tritium concentration acts as an emitter of μt into the adjacent fusion layer of D_2 (or D_2/T_2), where the fusion takes place. The third layer degrades and separates alphas and mu-alphas by the difference in the stopping powers. Since the molecular formation and fusion reactions are spatially confined to the fusion layer, we can control the processes involving alpha and mu-alpha such as energy loss and stripping, without affecting the kinetics leading to fusion. Information on initial sticking and stripping can thus be obtained.

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