DOE/ER/40333-147

C00-2197-147

TECHNICAL PROGRESS REPORT

EXOTIC ATOMS

By

Raymond Kunselman

University of Wyoming

Laramie, Wyoming 82071

February 1, 199⁴~~5~~ - January 31, 199⁵~~6~~

Prepared for the Department of Energy
under Contract #DE-FG02-87ER40333

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

EXOTIC ATOMS:

ABSTRACT.

The experiments use a variety of hydrogen isotopic mixtures to form solid targets for muons to produce muonic hydrogen isotope atoms that escape into vacuum. The method relies on transfer of the muon from a proton to either a deuteron or a triton. The resulting muonic deuterium or muonic tritium will not immediately thermalize because of the very low elastic cross sections (RT effect), and are emitted from the surface of the layer. A second solid hydrogen isotopic target is produced downstream on which the muonic hydrogen atom can react. 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 fusion. Our interest is the nuclear physics reaction rates and to use the muonic hydrogen isotopes in vacuum for energy level measurements. The method uses time of flight and is reminiscent of double scattering experiments.

Two other experiments are in the development stages. First to measure the energy dependence of the Ramsauer-Townsend cross section in tritium where it has not been measured. The measurements would be compared to deuterium and calculations. Second, kaonic atoms, hypernuclei, and kaon-nucleon scattering at DAPHNE.

1. Muonic Atoms into Vacuum from Solid Hydrogen

The present progress report will discuss the recent efforts since the last progress report and the survey presented for the review panel. The time at TRIUMF during the sabbatical leave has been enjoyable and productive and I have worked closely on all aspects of the experiment but especially the data analysis. This is a part of the experiment easily transported to the University of Wyoming campus.

Recent calculations exist [M.P. Faifman and L.I. Ponomarev, Phys. Lett. B 265, 201 (1991)] 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 D₂. The source of μt is the RT emitting hydrogen layer, protium with one part per thousand tritium ($c_t = 10^{-3}$). The experimental apparatus allows us to have the necessary flexibility to produce all desired targets in the vacuum region.

The main goal of the run which took place in July and August, was to collect data to determine the energy dependence and rate of μdt (muon, deuteron, triton) resonant formation as predicted by Faifman and Ponomarev. The principle is to use the time of flight of a μt atom emitted from an upstream emitting layer, which subsequently forms μdt and immediately fusions in a very thin downstream target layer of, in this case, pure D₂. Valeri Markushin completed a study of the process via Monte Carlo during a visit to TRIUMF in June. His simulations showed the advantage of using an overlayer of D₂ on the emitting layer. The target and detector geometry was optimized for this measurement.

First, the separation of the two gold foils (US=upstream and DS=downstream) was reduced from 39 mm to 18 mm, so lower energy muonic atoms would survive passage between them. The collimator, with hexagonal holes of dimension 3.0 mm and depth about 4 mm, could be inserted to be closer (3-4 mm) to the upstream foil in order to minimize the reduction of good alpha events from the downstream foil going toward the Si detectors.

Second, 50 mm diameter 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.

Several problems were encountered with the installations and testing of the new cryostat to get the complex system operational. The use of tritium of course added safety concerns. The system was checked with beam using deuterium which has been well studied by the group in the past.

Pure protium layers were measured to determine backgrounds and the US muon stop fraction. Emitting targets were deposited with and without collimator to determine the effect of each on various backgrounds in all counter systems.

More data was taken without collimator as the results were more "satisfying" in terms of event rate. The background data

taken without the DS deuterium layer was subtracted, after suitable normalization. The simple normalization was to GMU, and after accounting for the muon stop fraction in the US layer, the Si detector geometrical efficiency, and the fraction of GMU which were really muons entering the target region as opposed to beam electrons or muons stopping upstream, one arrives at a rate per muon stopping in the US emitting layer. The results per detector are approximately $25(2) \times 10^{-5}$ excess events remaining per muon stop (collimator out), with appropriate energy for the fusion alpha, and with TOF between 3 and 6 microseconds. The precision is dominated by the statistics of the background subtraction, so we are developing this more cleverly by a background parameterization. It is this TOF range which is expected to be dominated by resonant molecular formation, and in which we must look for structure corresponding to a resonance at 0.5 eV. For runs with collimator, the rates per muon stop are reduced by a factor of about 10.

Data was obtained with other target layers on the US cold foil. Thicker layers of deuterium were added to DS, to determine the total μ t flux at the DS layer. Several concentrations of tritium allowed variations for emission and pt transfer rate determination. 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 .

One unexpected feature of the data so far was 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 μ d 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.

We are considering the choices of where to proceed. Current thinking is to do a similar 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 DS target substrate, to increase our efficiency by a large factor. The problems we are anticipating are (1) making the Si work at 3K, and (2) 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 sections measurements and for alpha sticking of the muon in td fusion.

The data analysis has been carried out far enough to report definite evidence for the resonance effect. A variety of fits of the calculations to the data are being tried. The magnitude of the measured effect is half of that of the Monte Carlo calculations and

both experimental and calculational checks are being made. The competitor collaboration groups in Switzerland and Japan as well as the Russian theoretical groups are aware of the preliminary results of the unexpected discrepancy.

The emission of muonic deuterium and tritium from solid hydrogen is well established and becoming understood based on accepted cross sections and transfer rates. Detailed comparisons with Monte Carlo calculations are improving the precision. Several applications exist for muonic isotopic hydrogen atoms in vacuum.

2. Kaonic atoms, low energy kaon scattering, and hypernuclei

The first steps and actions are being made to join the collaboration from TRIUMF that will go to Frascati Lab for experiments with low energy kaon beams at the phi factory DAPHNE. The experiments would begin with hypernuclei and then go on to low energy scattering of kaons and kaonic atoms. The measurements would compliment each other. By being at TRIUMF I am readily available for the earliest planning stages.

The efforts with kaonic and sigma hyperonic atoms would include hydrogen targets as discussed previously for KAON at TRIUMF. The efforts on kaonic atoms will be to measure the atomic X rays from atoms formed with the negatively charged kaons. The X rays will be studied to determine nuclear distributions, to determine kaon-nuclear interaction parameters, and to test energy calculations. The X rays from sigmonic atoms are produced as a byproduct from kaon capture and are studied to determine the sigma-minus magnetic moment and mass. The first emphasis will be to measure the energy and line width of the 2p-1s transition of kaonic hydrogen which is directly related to the fundamental kaon-nucleon scattering length and will compliment low energy kaon scattering.

The techniques have largely been to utilize some form of an exotic atom as a laboratory tool, whether the goal was information concerning questions to do with particle physics, nuclear physics, atomic physics, or solid-state physics. The outgrowth of one measurement has led to further measurements so that exotic atoms connected to questions of lepton conservations, and then to questions with mu catalyzed fusion.

Publications

C00-2197-147 "Exotic Atoms," R. Kunselman, Technical Progress Report, 1993.

C00-2197-148 "Muon catalyzed fusion at very cold temperature: a new target system," F. Mulhauser, J.M. Bailey, G.A. Beer, J.L. Beveridge, M. Fujiwara, T.M. Huber, R. Jacot-Guillarmod, P. Kammel, N.P. Kherani, P.E. Knowles, S.K. Kim, A.R. Kunselman, G.M.

Marshall, G.R. Mason, A. Olin, C. Petitjean, C. Piller, and J. Zmeskal, presented at the Western Regional Nuclear Physics Conference, Lake Louise, February, 1994.

COO-2197-149 "Muon catalyzed fusion with a muonic tritium beam," P.E. Knowles, J.M. Bailey, G.A. Beer, J.L. Beveridge, M. Fujiwara, T.M. Huber, R. Jacot-Guillarmod, P. Kammel, N.P. Kherani, S.K. Kim, A.R. Kunselman, G.M. Marshall, G.R. Mason, F. Mulhauser, A. Olin, C. Petitjean, C. Piller, and J. Zmeskal, presented at the Western Regional Nuclear Physics Conference, Lake Louise, February, 1994.

COO-2197-150 "Direct thickness measurement of solid hydrogen target via alpha particle energy loss," M. Fujiwara, J.M. Bailey, G.A. Beer, J.L. Beveridge, T.M. Huber, R. Jacot-Guillarmod, P. Kammel, N.P. Kherani, P.E. Knowles, S.K. Kim, A.R. Kunselman, G.M. Marshall, G.R. Mason, F. Mulhauser, A. Olin, C. Petitjean, C. Piller, and J. Zmeskal, presented at the Western Regional Nuclear Physics Conference, Lake Louise, February, 1994.

COO-2197-151 "Muon catalyzed fusion of deuterons and tritons," G.R. Mason, G.A. Beer, P.E. Knowles, A. Olin, J.L. Beveridge, G.M. Marshall, F. Mulhauser, M. Fujiwara, N.P. Kherani, J.M. Bailey, T.M. Huber, R. Jacot-Guillarmod, C. Piller, P. Kammel, J. Zmeskal, S.K. Kim, and C. Petitjean, presented at the CAP Congress, Regina, June, 1994.

COO-2197-152 "Muon catalyzed fusion with a muonic tritium beam," G.A. Beer, M. Curran, J. Douglas, P.E. Knowles, G.R. Mason, A. Olin, J.L. Beveridge, G.M. Marshall, F. Mulhauser, M. Fujiwara, N.P. Kherani, T.M. Huber, C. Steffens, A.R. Kunselman, A. Adamczak, J.M. Bailey, M. Faifman, V. Markushin, R. Jacot-Guillarmod, C. Piller, P. Kammel, J. Zmeskal, S.K. Kim, V.S. Melezhik, and C. Petitjean, presented at CAM-94, Cancun, Mexico, 1994.

COO-2197-153 "Exotic Atoms," R. Kunselman, Continuation Proposal Submitted to the Department of Energy, 1993.