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TECHNICAL PROGRESS REPORT

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Exotic Atoms:

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Hadronic and Muonic Atoms 1969-1997

By

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ABSTRACT

Since this is a terminal progress-report it is a synopsis over the total time of the grant. I have utilized exotic hadronic and muonic atoms as tools to access information concerning questions to do with particle, nuclear, and atomic physics. The information has answered fundamental questions about lepton conservations, quark models, tests of the CPT theorem, QED energies, and nuclear structure. The present experiments involve reactions with a variety of hydrogen isotopic mixtures to 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

The nuclear atom was discovered at the start of this century and is a part of matter that is at a unique position between levels of microscopic and sub-microscopic structure. Atoms make up the level of common everyday matter and atoms are affected by the lower levels of matter such as nuclei and quarks which humans do not directly experience. The simplest atom is the hydrogen atom of one electron and one proton, and hydrogen was a fundamental system that was understood before proceeding to other atoms. An electron of an atom can be replaced with negative hadrons or muons and one can study exotic forms of the common hydrogen atom called hadronic and muonic atoms.

The production of the hadrons and muons requires high energy and they are produced at accelerator facilities where the experiments are conducted. The physicists wishing to conduct an experiment must present and defend a proposal before a committee, in order to be given a chance to use the expensive accelerator beam time. The cyclotron beam will be on continuously for 24 hours per day for the allotted time. Hence seldom can one individual conduct the whole experiment. The process is competitive and collaboration groups form to conduct the experiments.

The laboratory facility provides generalized electronic equipment, computer facilities, beam magnets, technician help for the laboratory equipment, and the main cyclotron proton beam. The protons hit a target and produce a secondary beam which the collaboration group must optimize with a magnet system leading to their experimental apparatus. The collaboration must have

submitted separate proposals to obtain grant money to purchase necessary specialized apparatus, pay graduate research assistant salaries, and for travel expenses. The apparatus is not the responsibility of the laboratory facility to maintain. The collaboration group divides their manpower into shift groups for the duration of the beam time to get the experiment working, monitor the progress, and to obtain the amount of desired data.

After the data is obtained, it is analyzed, and compared to predictions. Interesting results are published and new ideas are planned for further experiments.

In order to collaborate on these exotic atoms experiments I travel to the facility when we are allotted time to use the accelerator beam for our particular experiment, and I spend an extended period of time at the laboratory during summers and sabbaticals. I help in development of new apparatus, collect data during beam time, and analyze data. A longer stay at a facility allows contributing, interacting, and enjoying the experiment in a more relaxed manner than a short stay.

I teach courses that benefit from the experiments and help disseminate scientific and technical information back to the University. My department benefits both from the teaching and research aspects, since I teach courses using the results from fundamental research. I have a chance to apply my knowledge and skill and to learn new things. A non-negligible benefit is the opportunity to attend specialized seminars and colloquia not available at the University of Wyoming.

Physics being addressed/summary:

When a negative elementary particle replaces an electron it produces an exotic atom and the particle cascades toward the nucleus emitting measurable X rays. Muons, pions, kaons, anti-protons, and sigma-minus hyperons are most readily available for exotic atom production.

Over the period of time from 1969 to 1997 I have participated in a range of nuclear science activities and measurements using exotic atoms as a tool to study fundamental questions. These have included nuclear interactions, size determinations, measurements of particle properties, lepton conservation violations, and muon catalyzed fusion reactions of hydrogen isotopes. The accelerator facilities utilized include the Boulder cyclotron, Argonne National Laboratory, Brookhaven National Laboratory, Space Radiation Effects Laboratory in Virginia, Rutherford High Energy Laboratory in England, the Berkeley Bevatron, LAMPF in New Mexico, and TRIUMF in British Columbia.

The experiments included the anti-proton magnetic moment determination as a check on the fundamental CPT theorem, the muonium conversion to anti-muonium search for lepton conservation violation, and the sigma-minus magnetic moment measurements to test quark models. Other measurements included the low energy nuclear excitation-function and cross-section measurements of hydrogen and helium isotopes on medium Z nuclei, and muonic hydrogen isotope production and scattering that includes the present muon catalyzed fusion experiments. Several experiments were part of the dissertation topics for graduate students.

After arriving at the University of Wyoming, I formed a group along with several graduate students to collaborate at the University of Colorado cyclotron in Boulder. When I obtained large grants and could collaborate at National and International accelerator facilities the low energy experiments tapered away. I have found a way to do some local research to apply to Wyoming problems. I use X-ray fluorescence for non-destructive chemical analysis of selected materials. Most of the analyses have involved the trace element composition of archaeological obsidian artifacts which leads to prehistoric cultural behavior.

Highlights/accomplishments:

1. Kaonic atoms:

The kaonic atoms experiments begun at the Bevatron in Berkeley continued after I came to UW. They were the first experiments with kaonic atoms, hence we were able to do a survey of the elements to see which transitions were eliminated by nuclear absorption. The analysis we used was an optical model potential which connected to scattering results. Scattering experiments were unable to make measurements at zero energy and had an ambiguity in the sign of the resulting scattering length. On the other hand exotic atoms interactions are at such a negligibly low energy that it is treated as zero energy. The exotic atoms results tie in nicely with scattering results.

The measured x-ray energies allowed a direct measurement of the kaon mass, and I analyzed and published a first result. After that the collaboration groups have measured the kaon and various other masses with increasing precision.

2. Low energy nuclear reactions:

The collaboration group with several UW graduate students for experiments at the Boulder cyclotron was successful and resulted in several dissertations. An interesting feature was that the graduate students designed several items of apparatus. Some decays are very short, a few seconds, and a pneumatic system

blew the targets enclosed in a polyethylene holder through a tube connecting the radiation and measurement areas. The holders called 'rabbits' were machined at the UW shop. We were fortunate to find a Boulder collaborator Clyde Zaidins which simplified using the facility. He is an excellent physicist and the students and I learned a great deal because he was trained at California Institute of Technology in low-energy nuclear physics. I was trained in medium and high-energy physics at UC Berkeley and the electronics and detectors I had learned about proved useful.

3. Pionic atoms:

The pionic atoms experiments led to measurements of the pion-nuclear strong interaction and optical model studies, atomic structure affecting the cascade transitions, the neutron isotope shift and nuclear neutron distribution, the relativistic fine structure splitting as a test of the relativistic Klein-Gordon equation, the electron screening effects on transition energies, and nuclear resonance effect on transitions. In hydrogen and deuterium the strong interaction shift of the transition energy was related to the s-wave scattering length. The strong interaction in high Z nuclei confirmed the presence of the interaction even though it became a weak transition and difficult to measure because of nuclear capture from the upper state. The experiments utilized GeLi detectors, bent crystals, SiLi detectors, or foil absorption for the measurements. At TRIUMF we studied pionic atoms of lead(208) and bismuth(209), and used a BiGeO₄ Compton suppression detector constructed at TRIUMF.

The LAMPF (Los Alamos Meson Physics Facility) pionic atoms data of nickel isotopes and nearby nuclei were near to the end of the 3d-2p transition series and were useful for studying strong-interaction parameters and neutron radii. We studied two nearby calcium and titanium, and chromium series of isotopes for the 3d-2p transitions. The measurements determined nuclear interaction parameters and the nuclear neutron radii.

We used the good resolution from bent crystal measurements of the pionic hydrogen and deuterium 2p-1s transition to determine the scattering lengths. We did bent crystal energy measurements of pionic atoms to test the relativistic wave equation.

4. Muonic atoms:

The muonic atoms with complex nuclei such as Ce, Dy, Hg, and Pb led to measurements of nuclear properties. These included E2 and E4 moments, charge distributions, quadrupole moments, QED measurements, and nuclear polarization measurements. The key

that made these measurements easier and more reliable was the ability to include transitions to the 2s state which is usually as sensitive as the 1s state because it is less complicated in structure and easier to unscramble.

5. Anti-proton atoms:

The antiprotonic atoms experiments led to measurements of the mass, the strong interaction effects with the nucleus, and the magnetic moment. The magnetic moment measurement was a check on the CPT theorem. The analysis with an optical model potential was adequate to unscramble complex spectra.

6. Sigma-minus atoms:

Low energy sigma-minus hyperons are produced as a side effect of nuclear capture of the a kaon after it cascades and produces X rays. The sigmas are slowed and capture in the same target. These atoms produce sigmonic X rays which over the years have led to measurements on the strong interaction, the magnetic moment, and the mass. The key thing was a tagging procedure using the other decay product to reduce background compared to signal. This tagging made accurate experiments possible.

Several results have come from the measurements on hadronic atoms at BNL. The magnetic moment of the sigma-minus hyperon was determined from measurements of the fine structure splitting of X-ray transitions and the results compared to quark model predictions. Precision determination of atomic transition energies were used to extract the masses of the negative kaon and negative sigma hyperon. The strong interaction between the sigmas and the nuclei caused energy shifts and line broadenings that we measured and compared to theory.

7. Muonium conversion to anti-muonium:

We developed a technique for making thermal muonium into a vacuum by capturing an electron from a special SiO_2 material. Previous groups used a gas rather than a vacuum and the collisions complicated the interpretation of observations. We looked in the vacuum region for conversion of muonium with a mu-plus to anti-muonium with a mu-minus as a check on additive lepton conservation. The muonium could convert to antimuonium in the field-free vacuum region. A radiochemical technique was used to establish the presence of the mu-minus. The radioactive target was removed to an off-line counting location. The reaction of mu-minus on $\text{W}(184)$ produced $\text{Ta}(184)$ which has an 8.7 hour half-life. The Ta decayed by beta emission to excited states of W. The required triple coincidence signature was (1) a

beta, (2) a gamma of 414 keV (the cascade produces 91% through this transition), and (3) a second gamma of any of the several other energies which exist in the spectrum of the W daughter. A low background counting area was set up and used for tests of W targets that had been placed in a mu-minus beam to produce the radioactivity for testing the triple coincidence and the chemical procedures. Our published value was $G \leq 0.28 G_F$ (B.R. $\leq 2 \times 10^{-6}$). The data was used for the dissertation of Tom Huber who has continued to collaborate at TRIUMF. Considerations to improve this conversion experiment enough to attempt another try at finding the reaction or reducing the branching rate limit are being made.

8. Muonic hydrogen isotopes:

This section will be longer because these are the active experiments at Triumf (Tri-Universities Meson Facility). They are studies with muonic-hydrogen isotopes that have included production rates into vacuum, scattering cross-sections, and muon catalyzed fusion (μ CF) reactions. They were begun in 1990 and will continue several more years because of our vacuum region advantage compared to previous experiments which were into gases where collisions confused the measurements and interpretations.

The recent beam time was requested and approved by the TRIUMF Experimental Evaluation Committee in December 1996 at high priority. The beam time was made available in January 1997. The collaboration had found the Ramsauer-Townsend effect for muonic-deuterium scattering on hydrogen in August 1996. We were in a position to find the Ramsauer-Townsend effect for muonic-tritium scattering on hydrogen. Tritium is a radioactive health hazard and in the last few years we have developed a unique cryostat target allowing production of all possible muonic hydrogen isotopes that includes the necessary exhaust fans and safety measures when dealing with tritium.

Primary and secondary targets of all possible isotope targets can be made to study scattering and muon catalyzed fusion reactions. We have been approved for measurements of the probability of a muon sticking onto helium fusion products after a fusion reaction. This nuclear interaction information is useful for applied physics and practical developments by plasma physicists. Our research continues to be pure nuclear physics and we have no present intentions directed to energy source development.

It is interesting to note that the collaboration group at TRIUMF continues to grow as we continue the experiments of muon catalyzed fusion. We now have experts in fusion who formerly were competitors. We have been fortunate to obtain several Russian and Polish scientists who we can obtain NATO funds to

support, two post-docs and a faculty member from the University of Fribourg, and the assistant director of physics at the Swiss national accelerator facility.

The muonium production method developed from the muonium conversion experiment and apparatus. A beam of muons is brought into a solid ice hydrogen target which is mostly protium but if desired will be constructed with small amounts of deuterium or tritium. The muon captures on the protium and quickly transfers to a heavier isotope if present. The muon transfers because it is more bound to a heavier nucleus. The excess energy appears as kinetic energy of the muonic hydrogen atom. The atom drifts and loses energy from collisions. The cross-section is a resonance function of energy and becomes very small (Ramsauer-Townsend effect) before thermalizing.

The atom is allowed to drift into a vacuum region and can be used for experiments on production rates, precision energies of interest in fusion, muon catalysis, and atomic-state QED energies. A second solid hydrogen isotopic target can be produced downstream on which the muonic hydrogen atom can react and the time of flight measured and the energy determined. The two targets can be referred to as a production or emitter target of μp , μd , or μt , and the second as a reaction target to study the muonic atom beam. It is possible to use the time of flight between the emitter and the reaction target to characterize the energy dependence of reactions.

Calculations have become available for the rate as a function of energy in the interactions

where x is p, d, or t and X is the corresponding atomic form, P, D, or T. 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 happened that the μt kinetic energies required to satisfy the resonance condition coincided remarkably well with the emission energy spectrum of our target. Furthermore, the calculated rates were large enough to dominate the cross section for elastic scattering of μt by deuterons, the main mechanism for energy loss. This meant that the resonant interaction could be observed by passing muonic tritium of the appropriate energy through a thin layer of HD or D₂. The source of μt was the R-T emitting hydrogen layer, protium with one part per thousand tritium ($c_t = 10^{-3}$). This is expected to be the reaction that would be useful for energy production if a condition is found to allow muons to catalyze more reactions before decaying. The condition would probably be a technique to reduce muon sticking

to helium nuclei after fusion.

For each individual muonic hydrogen isotope 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 concentrations we use. 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 hydrogen isotope of μp , μd , or 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.

The knowledge of cross sections for scattering of μp , μd , and μt 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.

FUNDING SUPPORT (1969 - 1997):

There have been several small and several large grants over these years. The learning to write grants proposals on the small early grants was a useful experience and exercise. The small grant money provided some travel for me and travel for the early graduate students to the nearby University of Colorado cyclotron at Boulder where we collaborated on several experiments.

Small grants:

- 1971 Nuclear reactions and Mesonic Atoms, Philosophical Society \$600
- 1970 Mesonic Atoms, Sigma Xi, Wyoming Chapter, \$300
- 1970 Mesonic Atoms and Nuclear reactions, Sigma Xi, National Committee, \$200
- 1970 Nuclear structure and Hadronic Atoms, Research Corporation, \$3500

Large grants:

1996-1997 Muon Catalyzed Fusion and Exotic Atoms, D.O.E. \$15,000

1991-1995 Exotic Atoms, D.O.E. \$30,000, \$30,000, \$30,000,
\$30,000, \$30,000

1986-1990 Hadronic Atoms and Leptonic Conservations, D.O.E.,
\$53,000, \$55,000, \$50,000, \$65,000, \$30,000

1977-1985 Mesonic Atoms, D.O.E., \$60,000, \$60,000, \$68,000,
\$38,000, \$45,000, \$48,000, \$56,000, \$55,000, \$57,500

1974-1976 Mesonic Atoms, E.R.D.A., \$52,000, \$47,000, \$55,000

1971-1973 Mesonic Atoms, A.E.C., \$11,000, \$19,000, \$48,000

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