Laser-induced spin-polarization of exotic atoms involving muons for a bright muon source

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The invention of lasers has proved to be a ground breaking success in the field of science. Their novel properties such as coherence, tunability, ability to reach high power and to be transformed into various pulse-shapes, has led to a wide variety of applications in industries and medical and applied science. To count a few, these applications include laser cutting, laser welding, lithography, interferometric techniques, spectroscopic techniques, probing and micro-processing of advanced materials, optical imaging techniques such as MRI and tomography, laser-based surgery and so on. The cutting-edge research in the field of atomic, molecular and nuclear physics, also relies on lasers. The internal structure of atomic and molecular systems have been studied by various types of laser driven optical spectroscopy. Interesting and useful dynamics involving laser-matter interaction such as the electronically induced transparency, coherent population trapping, lasing without inversion, etc. have been discovered and have led to the development of new optical devices and applications. The laser-matter interaction is also essential in the development of modern theory and various important experiments involving subatomic particles.

The muon, μ^- (or μ^+, which is the antiparticle of muon a.k.a antimuon) which is an elementary particle similar to the electron, with the same charge and spin, but the mass about 200 times than that of the electron, is of great significance in the research communities worldwide currently. Due to its easy availability, higher mean lifetime (2.2μs) than other unstable particles, high penetration depth into matters, muon is very useful in various insightful experiments such as μSR experiment, muon-catalized fusion, etc. In J-PARC (Japan Proton Accelerator Research Complex) facility, the proton beam from the 3 GeV Rapid Cycling Synchrotron (RCS) is utilized to create beams of positive/negative muons, (kinetic energy typically a few MeV). In order to be used for further studies, the positive or negative muon beam, in general, has to be slowed down by passing through certain medium, thereby forming atomic muonium (μ^+e^-) or muonic hydrogen ($p\mu^-$) and losing their spin-polarization. These kind of atoms are popularly known as exotic atoms, in which one or more sub-atomic particles have been replaced by other (usually unstable) particles of the same charge. Towards fulfilling the high demand for a slow bright muon source with high spin-polarization, there are various technical challenges related to ionization of muonic atoms and restoring polarization. In this thesis, we report our theoretical work involving laser-induced processes in the direction of achieving efficient spin-polarized muon source, that will serve as a guide to the experimentalists.

In the first work, we deal with the ionization efficiency of Doppler broadened muonium atoms. After ejection from the particle accelerator, muons with 100% spin polarization and very high kinetic energy are slowed down by going through a thin tungsten film medium, capturing electrons to form muonium atoms. This results in loss of degree of polarization down to $\sim 50\%$ as well as emergence of extremely broad Doppler width ~ 230 GHz because of the high temperature ($\sim 2000°$C) build-up due to collision. To remove electrons from slow muoniums, the ionizer laser system has been developed at RIKEN for the MLF (Materials and Life Science Experimental Facility) of J-PARC. The ionization process follows a one-photon resonant two-photon ionization process via resonance at $2p$ state using nanosecond 122 and 355 nm pulses of pulse duration 2 ns. We address the question as to whether the transform-limited or broadband nanosecond pump pulse is more favorable to efficiently pump and subsequently ionize Doppler-broadened atoms, and under what condition. Using a semi-classical set of density matrix equations under the dipole approximation, slowly varying envelope and the rotating wave approximations, we numerically calculate the Doppler-averaged ionization yield of the muonium atoms for various pumping intensities over the range of low to high intensity regimes of the ionization pulse. Under the huge Doppler-broadening, one may naively guess that the broadband nanosecond pump pulse may be much more efficient to produce ions as the broadband pump pulses cover broader velocity range of atoms. However, it turns out that the transform-limited pump pulse is more efficient in the two regimes, i.e. *weak pumping regime* and *strong ionization regime*. The weak pumping regime is a trivial case, where at low pumping intensities, no matter what ionization intensity is, the introduction of a broad bandwidth in pump pulse always hampers its pumping efficiency due to loss of coherence, leading to lower ionization yield. The most efficient way is the use of a transform-limited pump pulse to coherently pump the atoms to excited state along with a strong ionizing pulse for rapid ionization from the excited state. On the other hand, if the pump pulse intensity is beyond the weak pumping regime and the ionization pulse intensity is moderate, the use of broadband pump pulses can result in better ionization efficiency.

In the second work, we focus on the prospects of improvement in nuclear-spin polarization of muonium atoms by introducing chirp in the circularly polarized laser pulses. By numerically solving a set of density matrix equations involving the hyperfine states of the muonium atom, we find that a chirped 1 ns pulse with a *narrow* bandwidth instead of a broad bandwidth efficiently induces a resonant pump and following dump processes within a single laser pulse, thereby transferring the angular momentum of the circularly polarized pump pulse to the atoms, which leads to the higher degree of nuclear-spin polarization. For muoniums at rest, a single chirped 1 ns pulse with a 4 GHz bandwidth and peak intensity of 2×10^6 W/cm^2 leads to 43% of nuclear-spin polarization, which is compared with 33% of nuclear-spin polarization by the transform-limited 1 ps pulse or chirped 1 ns pulse with a 400 GHz bandwidth for both. We also find that an introduction of the chirp does not help in the presence of significant Doppler broadening. This means that the use of chirped laser pulses is beneficial for the atomic beam at the cross-beam geometry, where the influence of Doppler broadening is negligible, and similarly, if a slow muonium beam is realized in the future to nearly eliminate Doppler broadening, then chirped laser pulses would be useful to attain a higher degree of nuclear-spin polarization.

In the third work, we shift our focus to the negative muon (μ^-). As compared to positive muon (μ^+), the progress in production of a slow polarized μ^- beam is less. μ^- after being captured by a proton forms muonic hydrogen atom which has modified electronic structure compared to the hydrogen atom, due to the heavier weight of μ^- than electron. Muonic hydrogen is very popularly utilized in spectroscopy experiments to precisely measure the size of the proton which is a long existing challenge in the scientific community. Pohl's group in PSI (Paul Scherrer Institute) performed the pioneering experiment which involved measurement of Lamb shift ($2S_{1/2} - 2P_{1/2}$ energy difference) and reported that the proton radius is about 4% smaller than the widely accepted value. An independent measurement of the hyperfine splitting ($1S(F = 0 - F = 1)$) of the ground state of muonic hydrogen can also serve as a pathway to accurately determine the proton as proposed originally by Bakalov's group. Although the $1S(F=0)-1S(F=1)$ transition of muonic hydrogen is large compared to ordinary hydrogen for easier measurement, this transition is dipole-forbidden and we need to employ the magnetic dipole transition which is several orders of magnitude weaker than the electric dipole transition. Assuming a long laser pulse at 6.76 μm and 0.25 mJ pulse energy, Adamczak's group have found that the excitation probability is only 1.2×10^{-5}, which is too low for the proposed experiment to be feasible. They have also proposed a technique of introducing a multipass cavity to increase the excitation probability up to 12% which is very challenging task. This brings the motivation to study how would the excitation probability of the hyperfine ground state of muonic hydrogen vary for different pulse durations. Specifically, we compare the cases of 20, 2, and 0.2 ns pulses with a Gaussian temporal shape such that the pulse bandwidth is, respectively, narrower than, comparable to, and broader than the Doppler width at 300 K. We numerically solve a set of density matrix equations to obtain the excitation probability at the various laser intensities and detunings. By studying the excitation probabilities and their lineshapes for the cases of 20, 2, and 0.2 ns pulses, we find that, at a moderate intensity, the 2 ns pulse, which means the pulse whose bandwidth is comparable to the Doppler width of the atoms, yields higher excitation probability than those by the 20 and 0.2 ns pulses and has its lineshape relatively narrow. This makes the 2 ns pulse as the best choice for spectroscopy experiment. Our study can serve as a guideline for the development of the relevant laser source, depending on the purpose is a precise measurement of the ground state hyperfine splitting of muonic hydrogen or production of spin-polarized muonic hydrogen.