Highly Polarized Muonic He Produced by Collisions with Laser Optically Pumped Rb

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We have formed highly polarized muonic helium by stopping unpolarized negative muons in a mixture of unpolarized gaseous He and laser polarized Rb vapor. The stopped muons form muonic He ions which are neutralized and polarized by collisions with Rb. Average polarizations for ^{3}He and ^{4}He of (26.8±2.3)% and (44.2±3.5)% were achieved, representing a tenfold increase over previous methods. Relevant cross sections were determined from the time evolution of the polarization. Highly polarized muonic He is valuable for measurements of the induced pseudoscalar coupling g_p in nuclear muon capture.

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Highly polarized atoms containing a muon are important laboratories for studying atomic and nuclear interactions [1]. For example, measurements on polarized muonium (μ^+e^-) of the ground state hyperfine splitting have yielded precise tests of QED [2]. A fundamental muonic system which has been difficult to polarize is muonic He. The spin dependence of the reaction $\mu^- + {}^3\mathrm{He} \rightarrow {}^3\mathrm{H} + \nu$ can provide an excellent means of determining g_p, the induced pseudoscalar form factor of the ^{3}He weak nuclear current [3]. Early efforts to measure g_p had limited sensitivity, however, due to low muon polarizations [4]. The original approach of stopping polarized muons in unpolarized He results in muon polarizations of only a few percent [5]. The alternative technique of stopping unpolarized muons in nuclear polarized ^{3}He also results in low polarization [6].

In this Letter, we present a new approach for producing polarized muonic He that yielded average polarizations of (26.8±2.3)% in ^{3}He and (44.2±3.5)% in ^{4}He. In contrast to earlier techniques [5, 6], neither the muons nor the He were polarized. Instead, the muonic He was polarized by collisions with laser optically pumped Rb. Polarization occurs during both neutralization and subsequent spin-exchange collisions. The cross sections of these processes are sufficiently large that with a Rb number density [Rb]$\sim 10^{15}$ cm^{-3}, both occur with time scales comparable to the 2.2 μsec muon lifetime. Indeed, we were able to measure the time evolution of the polarization and extract cross sections for the relevant atomic processes.

Critical to our experiment was the formation of the neutral paramagnetic atom $(\mu^-\mathrm{He})^+e^-$. A muon captured into an He atomic orbital will immediately Auger eject the two atomic electrons during its cascade to the ground state leaving a $(\mu^-\mathrm{He})^+$ ion. Because the muon mass is 206 times that of an electron, its Bohr orbit around the nucleus is quite small. Thus, the tightly bound $(\mu^-\mathrm{He})^+$ ion can be thought of as a *pseudonucleus*, with a net charge of +1, which behaves much like a proton. In 10 atm of He, the ion will form a molecular ion $\mathrm{He}(\mu^-\mathrm{He})^+$ in a few nanoseconds [7] much as H^+ would form HeH^+ [8]. We found that collisions with polarized Rb vapor were effective in dissociating the molecular ion [9] through the reaction

$$\mathrm{Rb}\uparrow + \mathrm{He}(\mu^-\mathrm{He})^+ \rightarrow \mathrm{Rb}^+ + \mathrm{He} + (\mu^-\mathrm{He})^+e^-\uparrow, \quad (1)$$

where the arrows indicate the spin polarization of the transferred electron. Immediately after the dissociative charge exchange collision (1), the hyperfine interaction couples the pseudonucleus to the polarized electron thereby polarizing the muon.

Once the neutral atom $(\mu^-\mathrm{He})^+e^-$ is formed, it is further polarized by spin exchange collisions with Rb:

$$\mathrm{Rb}\uparrow + (\mu^-\mathrm{He})^+e^-\downarrow \longrightarrow \mathrm{Rb}\downarrow + (\mu^-\mathrm{He})^+e^-\uparrow, \quad (2)$$

where the arrows denote the polarization directions of the unpaired electrons. This reaction is virtually identical to Rb-H spin exchange [10]. After the short-lived collision which affects only the spin of the valence electrons, the polarization is shared with the pseudonucleus.

Before we performed our experiment, it was unclear whether reaction (1) would neutralize the $(\mu^-\mathrm{He})^+$ ions sufficiently rapidly. Historically, Xe has been used to neutralize $(\mu^-\mathrm{He})^+$ ions [5]. Large quantities of Xe are required since this is only energetically possible if neutralization occurs before molecular ion formation. Unfortunately, Xe, which is strongly depolarizing to Rb, hinders optical pumping [11]. We therefore tried a nondepolarizing electron donor, methane [12], which neutralizes the $(\mu^-\mathrm{He})^+$ ion by the simple charge transfer reaction

$$\mathrm{CH}_4 + (\mu^-\mathrm{He})^+ \longrightarrow \mathrm{CH}_4^+ + (\mu^-\mathrm{He})^+e^- . \quad (3)$$

At sufficient density, CH_4 can neutralize the $(\mu^-\mathrm{He})^+$ ion in a few nsec, a time short compared to that for (1) or (2). When sufficient CH_4 is present that (3) dominates neutralization [13], the neutral muonic He atoms are formed unpolarized so only reaction (2) will govern their polarization.

The experiment was performed at the Los Alamos Clinton P. Anderson Meson Physics Facility (LAMPF). Negative muons were stopped in spherical glass target cells, ~2.5 cm in diameter, containing about 8 atm of He, a few mg of Rb metal, 75 torr of N_2, and in some cases up to 250 torr of CH_4 (all pressures are quoted at room temperature). The cells had wall thicknesses of about 100 μm to allow the low momentum (23 MeV/c) muons to penetrate the glass. A novel beam tune, discussed elsewhere, was required to stop the muons in these small and relatively thin targets [6, 14]. The targets were kept at approximately 200 °C to maintain [Rb]=$(4.37\pm0.80)\times 10^{14}$ atoms/cm^3. To determine [Rb], we polarized the ^{3}He nuclei by spin exchange with the polarized Rb vapor [15, 16] and compared the nuclear spin relaxation rates in the absence of laser light at 200 and 25 °C. The difference of the two rates is $\langle\sigma v\rangle$[Rb], where $\langle\sigma v\rangle$ is the velocity averaged Rb-He spin-exchange cross section. Our error in [Rb] is dominated by the uncertainty in the measured value of $\langle\sigma v\rangle = (1.2\pm0.2)\times10^{-19}\mathrm{cm}^{-3}\,\mathrm{sec}^{-1}$ at 200 °C [16, 17]. The Rb was optically pumped with 5 W of circularly polarized 795 nm light from a Ti:sapphire laser. At this optically thick [Rb], the cell contains a region which is nearly 100% polarized, while the remainder is unpolarized [18]. The size and shape of the polarized region was monitored with two charge-coupled-device (CCD) cameras which recorded cross fluorescence from the polarized Rb at 780 nm. A vertical $\sim$ 1 G magnetic field provided a quantization axis for the Rb spins.

The direction of the Rb polarization, and consequently the muonic He polarization, was reversed every 2 min by rotating a quarter-wave plate which flipped the helicity of the laser light. Incoming muons were tagged by thin scintillators and muon decay electrons were detected by two scintillation telescopes positioned above and below the target. The muon polarization was determined by the up/down asymmetry in the decay electrons,

$$A(t) = \frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}}, \quad (4)$$

where $N_{\uparrow\uparrow}$ ($N_{\uparrow\downarrow}$) is the number of decay electrons emitted parallel (antiparallel) to the Rb polarization direction, and t is the time between the formation of the muonic He

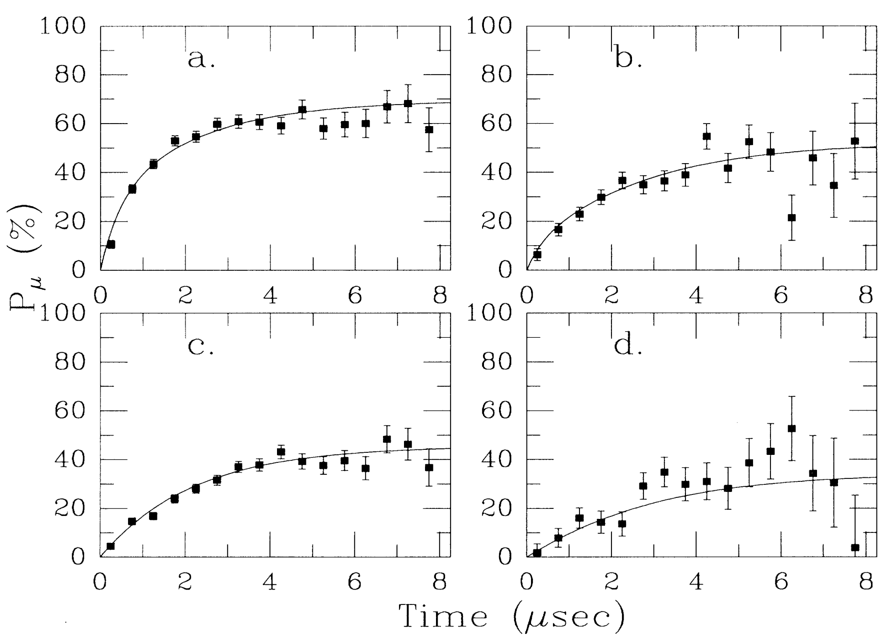

FIG. 1. Muon polarization as a function of time in muonic He. The four graphs correspond to four target cells: (a) ^{4}He without CH_4, (b) ^{3}He without CH_4, (c) ^{4}He with CH_4, and (d) ^{3}He with CH_4. The solid lines are given by (6) for (a) and (b), and by (5) for (c) and (d), where the numerical values of the parameters resulted from a global fit to all of the data (including the muonium data of Fig. 2).

ion and the decay of the muon. The muon polarization $P_\mu(t) = A(t)/f(t)a_e$, where a_e is the analyzing power which was evaluated by a Monte Carlo simulation. The quantity f, the fraction of decay electrons that come from muons stopped in He, accounts for the fact that muons can stop in glass or the other gases. We determined f by fitting the muon decay time spectrum with a sum of exponentials with time constants corresponding to the known muon lifetimes in the various target elements [6, 14]. From 15% to 30% of the decay electrons detected were from muons stopped in He.

In Fig. 1, we show $P_\mu(t)$ for four targets containing either ^{3}He or ^{4}He. For each isotope, we studied targets with and without CH_4. In all cases substantial polarizations result. There are three important features evident in the data. First, the saturation polarization in ^{3}He cells is about 75% that of ^{4}He cells. (Cells with and without CH_4 should be compared separately.) Second, for the targets without CH_4, the polarization increases much more quickly for ^{4}He. Finally, for both isotopes, the polarization increases faster in the cells without CH_4. In Fig. 2, we show the polarization as a function of time for muonium which was formed by stopping unpolarized *positive* muons in a target containing ^{4}He and CH_4 [19]. Note that the polarization saturates much more quickly than in the other data. We can understand all of these features in terms of two atomic interactions, spin exchange (2) and polarized charge exchange (1).

For simplicity, we first consider data from targets containing CH_4 in which spin exchange is the only polarizing mechanism. Starting from equation (VI.8) of Happer [12], it is straightforward, though cumbersome, to show that for each isotope α, the muon polarization has the form

$$P_\mu = P_\alpha^m \eta (1-c)(1 - h_\alpha e^{-t\beta_\alpha}), \tag{5}$$

where the subscript $\alpha = 3$ ($\alpha = 4$) for ^{3}He (^{4}He).

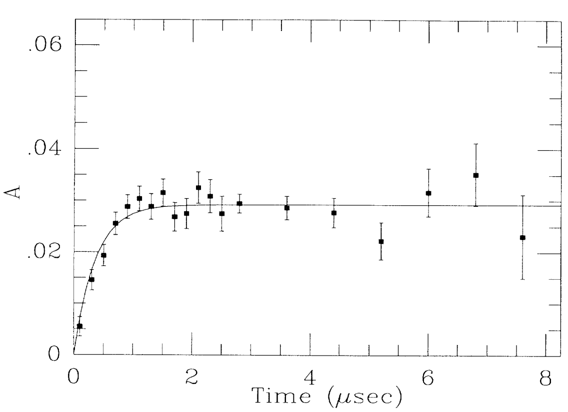

FIG. 2. The decay electron asymmetry (which is proportional to the muon polarization) as a function of time for muonium. The solid line is the function (5) using the parameters that resulted from the global fit.

The constant η represents the fraction of the muonic He atoms that are formed where the Rb is 100% polarized. The parameter P_α^m, the maximum theoretical polarization, is equal to 3/4 (1) for the case of ^{3}He (^{4}He). Note that for ^{3}He, the spin-1/2 muon must couple to the spin-1/2 ^{3}He nucleus and the spin-0 singlet state, which forms 25% of the time, cannot be polarized. The rate $\beta_\alpha = g_\alpha \sigma_{\rm SE} \bar{v}_\alpha$[Rb], where $\sigma_{\rm SE}$ is the electronic spin-exchange cross section which can be assumed to be velocity independent [12]. The cross section $\sigma_{\rm SE}$ is identical to the Rb-H spin-exchange cross section. The nuclear spin dependence is contained in g_α, where $g_4 = 1/2$ and $g_3 = 4/9$. Since the collisions are thermal, the relative velocity $\bar{v}_\alpha = \sqrt{8kT/\pi M_\alpha}$, where M_α is the reduced mass, k is Boltzmann's constant, and T is temperature. The parameters h_4=1 and $h_3 = 1 + t\beta_3/3$. The constant c accounts for the possibility of any competing reactions to (3) that result in diamagnetic species [20]. For muonium, the parameters are identical to those of ^{4}He with the exception of the reduced mass in $\bar{v}_\alpha$.

The equation that characterizes the polarization in targets without CH_4 is more complicated. Generalizing (VI.8) of [12] to include polarization that occurs during reaction (1) we find

$$P_\mu = P_\alpha^m \eta (1 - a_\alpha e^{-t\gamma_\alpha} - b_\alpha e^{-t\beta_\alpha}). \tag{6}$$

The quantity $\gamma_\alpha = \sigma_{\rm CE} \bar{v}_\alpha$[Rb] is the rate of neutralization through the process (1) where $\sigma_{\rm CE}$ is the dissociative charge exchange cross section. For ^{4}He, $a_4 = 1 - D_4/2$ and $b_4 = D_4/2$, where $D_\alpha = (1 - \beta_\alpha/\gamma_\alpha)^{-1}$. For ^{3}He we have the more complicated expressions $a_3 = 1 - 19D_3/27 + 5\beta_3 D_3^2/27\gamma_3$ and $b_3 = 1 - a_3 + 5D_3\beta_3 t/27$ which is time dependent [21]. It must be noted that for dissociative charge exchange $\bar{v}_\alpha$ is the relative thermal velocity between Rb and He$(\mu^-{\rm He})^+$, while for spin exchange it is between Rb and $(\mu^-{\rm He})^+ e^-$.

From Eqs. (5) and (6), we see that only four parameters characterize the polarization for the muonic He data: $\sigma_{\rm SE}$, $\sigma_{\rm CE}$, η, and c. A fifth parameter is required to characterize the saturation value for the muonium data because the stopping fraction is unknown. If we perform a single global fit of all of our data (Figs. 1 and 2) by (5) and (6) we find that

$$\sigma_{\rm CE} = (4.47 \pm 0.67 \pm 0.82) \times 10^{-14}\ {\rm cm}^2\,, \tag{7}$$

$$\sigma_{\rm SE} = (1.36 \pm 0.17 \pm 0.25) \times 10^{-14}\ {\rm cm}^2\,, \tag{8}$$

where the first error quoted is due to statistics, background correction, a_e and f, and the second is due to the uncertainty in [Rb]. The spin-exchange cross section measured here is consistent with calculations of the cross section for spin exchange between Rb and H [22]. The fitted value for η, 0.70 ± 0.10, agrees with estimates of the polarized volume based on the CCD camera images. For c, we find a value of 0.35 ± 0.10 indicating that competing reactions to (3) do indeed occur.

As an additional check, we have fitted both the muonium data and the data for the target containing ^{4}He and CH_4 to Eq. (5) to compare the spin-exchange rates. The ratio of the rates, with statistical error only, is 5.7 ± 1.0, in agreement with the ratio of thermal velocities, 5.8. We have also fitted all of the muonic He data letting the saturation values for the five data sets float separately. We find that the ratio of the saturation polarizations of muonic ^{3}He to muonic ^{4}He is 0.76 ± 0.03, consistent with 3/4, as expected.

In conclusion, we have shown that we can produce very high polarizations in muonic He through spin interactions with laser optically pumped Rb [23]. The atomic processes responsible have been quantitatively studied using a variety of targets that aided in isolating the different polarization mechanisms. The relative simplicity of our experiment ensures that our techniques will find future use. In fact, experiments to measure g_p based on this technique have been initiated at both LAMPF and TRIUMF [24].

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