attempted to vary possible surface or internal fields, which might arise from work functions, crystalline fields, or image charges, etc., by coating conventional carbon foils with thin layers of aluminum (which was permitted to oxidize) or gold. The increased energy loss of the ions upon passage through these foils slightly changed the period of the beats because of the consequent velocity decrease, but did not produce increased dephasing. This proves that the coated surface remained substantially intact during the life of the foil.

The magnitude of the relative orientation produced by the carbon foils was found to be about 20% larger than that observed with the gold-coated foils at 50 and 70 keV incident ion energies; at 70 keV the aluminum and carbon surfaces produced indistinguishable results. It must be noted in connection with these measurements that the vacuum was only of the order of 10^{-6} Torr, so surface-contamination effects cannot be excluded.

The general orientation and coherence of excited levels of fast ions and atoms can be used in atomic-structure investigations, such as $\Delta m = 1$ level crossing, particularly in ionic levels which are difficult to orient by other techniques.

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Muonium Formation in Noble Gases and Noble-Gas Mixtures*

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In an experiment at the Clinton P. Anderson Meson Physics Facility, no muonium formation was found in pure He or Ne, and abundant formation in Ar and Xe. A small Xe admixture (0.1%) in He and Ne resulted in abundant muonium formation, due to the process in which Xe serves as an electron donor to a low-energy positive muon. These results are qualitatively consistent with our knowledge of relevant atomic collision cross sections.

Muonium was discovered[1,2] by observing the characteristic muonium Larmor precession frequency when positive muons were stopped in pure Ar gas, and it was found that between 50 and 100% of the muons stopped in Ar form muonium. In subsequent magnetic-resonance experiments on muonium using Ar and Kr,[3,4] it was established that greater than 50% of the muons stopped in either Ar or Kr form muonium.

As muons slow down in a gas, the competition between electron-capture and electron-loss collisions with the gas atoms principally determines the fraction of the muons that form muonium. This fraction can be estimated from available data[5,6] and theoretical calculations[2,7] on capture and loss cross sections for muons and protons in noble gases. The calculations of muonium formation require simultaneous numerical integration of the differential equations[6] for the charge fractions of the muon beam and the energy loss (dE/dx). The cross-section data for protons below 0.7 keV and the dE/dx curve below 10 keV, as well as the applicability of proton results to muons, are not known well enough to enable quantitative predictions. Our estimates are less than 20% muonium formation in He, less than 40% in Ne, 70% to 90% in Ar, and 100% in Xe. Muonium atoms with less than about 50 eV will survive stably to thermal energy because the capture and loss reaction rates are very small below 50 eV. Muonium can be formed at thermal energy only in Xe, which is the only noble gas whose ionization potential is less than that of muonium. Our measurements on muonium formation by muons stopped in gases provide information not available from proton studies, and many types of atomic collisions from thermal energy to 100 keV contribute to the final result.

A study of behavior of positive muons stopped in liquid helium was done at the Space Radiation Effects Laboratory[8] and is reported in the following Letter. No muonium formation was found, and the muons behave in liquid helium both above and below the λ point as free, polarized muons.

In view of this interesting result, which differs so dramatically from the behavior of positive muons stopped in Ar or Kr gas, the experiment reported in this Letter was done to study the behavior of positive muons stopped in He, Ne, and Xe in order to provide a more complete understanding of muonium formation in the noble gases.

The method of our experiment is the classic one for studying the Larmor precession of free muons[9] (13.6 kHz/G) or of muonium[1] (1.40 MHz/G), which relies on the availability of polarized muons from pion decay and the correlation of the muon spin direction with the direction of emission of the positrons from muon decay.

Our experiment was done at the Clinton P. Anderson Meson Physics Facility (LAMPF), and indeed is the first muon physics experiment done at this new laboratory. The muon channel—a 21-magnet system—is basically of conventional design consisting of a pion collection, a pion decay, and an analyzer section.[10] The characteristics of the output muon beam are given in Table I.

A schematic diagram of the experimental arrangement is shown in Fig. 1. The high-pressure gas target contained internal scintillation counters. The gas was circulated over Ti at 750°C to remove impurities. The gases used were research grade with impurity concentrations below 1.0 ppm (except for Xe which had 5 ppm O_2). Three pairs of mutually perpendicular Helmholtz coils were used to null out the stray field, and an additional Helmholtz pair produced the precession field transverse to the muon spin. The field was measured with a Rb optical pumping magnetometer[11] and was homogeneous to 1%. The counters were plastic scintillators. Counter 5 was

TABLE I. Properties of μ^+ beam.

Proton energy	650 MeV
Proton current	1.5 μA, av
Duty factor	4.5%
Production target	6.0 cm C
μ^+ rate[a] (1·2)	23 500/sec, av
μ^+ stops[b]	930/sec, av
p_μ (backward decay)	93 MeV/c
$\Delta p_\mu/p_\mu$	±3%
Spot size[c]	250 cm^2
Polarization	(80 ±2)%
Impurities:	
π/μ	< 0.01
e/μ	0.03

[a]Rate into 280 cm^2, 38 cm from last quadrupole.
[b]50-atm He gas target: 0.22 g/cm^2; area, 320 cm^2.
[c]Full width at half-maximum at 75 cm from last quadrupole.

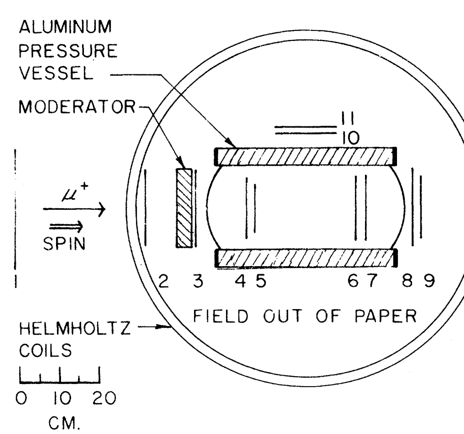

FIG. 1. Diagram of apparatus. The pressure windows were 4.76 mm thick.

0.012 cm thick to minimize stops in the scintillator which would count as stops in the gas, and its efficiency was $>50\%$. Muons which stopped in the target walls counted as μ_{stops} $(1\cdot 2\cdot 3\cdot 4\cdot 5\cdot \bar{6}\cdot \bar{7})$ and contributed a small background of free muon precession which was measured in vacuum runs. Curves of μ_{stops} versus gas pressure were taken to estimate the fraction of muons stopping in the walls. For the He and Xe runs, two thirds of the wall surface was lined with a scintillator which was optically coupled to counter 7. This additional veto cut the wall stop background in half.

The time distributions were taken with a CAMAC digitron clock. The signal μ_{stop} started the digitron counting a 100-MHz clock. Either E_f $[\bar{1}\cdot \bar{2}\cdot \bar{3}\cdot \bar{4}\cdot 6\cdot 7]$ or E_n $[\bar{1}\cdot \bar{2}\cdot \bar{3}\cdot \bar{4}\cdot 10\cdot 11]$ stopped the count. The digitized time was used to update a histogram in a PDP-11/20 computer. Two spectra, 90° out of phase, were thus obtained. Figure 2 shows time distributions for the E_f for Ne.

The essential data consist of time distributions which can be represented by

$$N(t)=N_0e^{-t/\tau}\times[1+A\exp(-t/\tau_D)\cos(\omega t+\varphi)+B], \quad (1)$$

where τ is the muon lifetime, τ_D is the depolarization time, A is the precession amplitude, ω is the precession frequency, φ is the initial phase, B is a constant background term, and N_0 is a normalization constant. Equation (1) was fitted to the time distributions. Free-muon precession runs were made at 60 G and muonium runs at 3 and 4 G. Pressures used were 50 atm He, 26 atm Ne, 30 atm Ar, and 4.4 atm Xe. Table II gives the target gas and the corresponding fractions of muons remaining free (F_μ) and forming muonium (F_M). These fractions are calculated from the values of A with corrections for counter geometry, absorption of low-momenta positrons, beam polarization, and background.

As Table II indicates, no muonium formation was found in pure He or pure Ne, while abundant formation was found in Ar and Xe. Due to inadequate gas circulation by a low-pressure pump used only for the 3-G Xe run, these data were taken with substantial O_2 contamination, which is known to depolarize muonium by electron-spin exchange collisions.[12] The 4-G run was taken with the pump used for all other runs, which reduced the O_2 content a factor of 2 during the run, and increased the muonium amplitude. The result quoted for muonium formation in Xe is an extrapolation to zero O_2-impurity content.

The results are more definitive, especially for Ne, than the theoretical estimates, indicating the need for better understanding of the low-energy collision processes. The fact that muons appear to be free, fully polarized particles in He or Ne might provide a useful approach to measuring the magnetic moment or other properties of the free positive muon, but the possibility of formation of the molecular ions[13] μ^+He or μ^+Ne must be considered.

In Ar and Kr the dominance of the electron-capture cross section leads to nearly 100% muonium formation at muon kinetic energies below 1 keV. In He and Ne we have found that muonium formation does not occur because the electron loss process dominates, and the muon is free in the gas and presumably thermalized. Only for Xe is electron capture energetically allowed at thermal energy. From our knowledge of the corresponding proton reaction[14,15] and theoretical calculations, we can estimate that the cross section for the electron-donor reaction

$$\mu^+ + \mathrm{Xe} \rightarrow \mu^+e^- + \mathrm{Xe}^+(^2P_{1/2} \text{ or } ^2P_{3/2}) \quad (2)$$

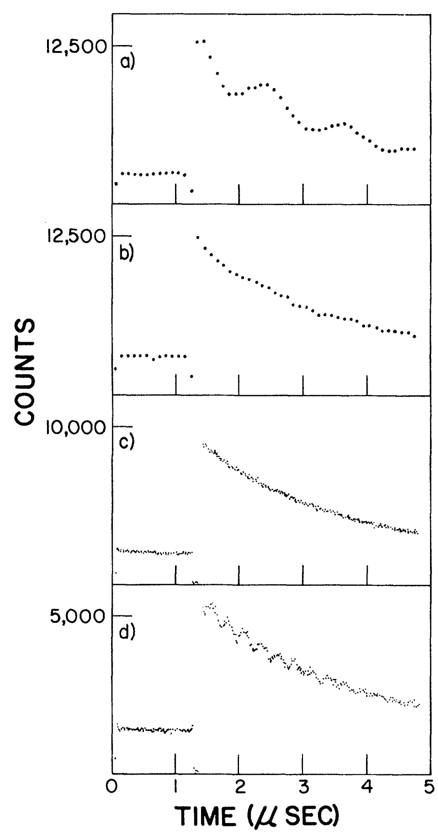

FIG. 2. Free-muon precession at 60 G (a) in pure Ne and (b) in Ne + 0.15% Xe. Muonium precession at 2.75 G (c) in pure Ne and (d) in Ne + 0.15% Xe.

TABLE II. Results on muonium formation.

Target gas	F_μ (%)	F_M (%)
He	99(5)	1(5)
He + 0.015% Xe	83(15)	
He + 0.09% Xe	25(9)	75(9)
Ne	100(2)	0(2)
Ne + 0.15% Xe	19(3)	81(3)
Ar	35(5)	65(5)
Xe	10(5)	100[a]

[a]No error estimate given.

will be of the order of 10^{-15} cm^2 from 1 keV to thermal energies. Hence with a Xe density of 10^{18}/cm^3 added to the high-pressure He or Ne (about 1 part in 10^3 Xe), the large electron-capture cross section from Xe leads to muonium formation for muon kinetic energies less than 50 eV.

Data were taken with gas mixtures with the results shown in Table II. Figure 2 shows the dramatic effect of an admixture of 0.15% Xe with Ne, which leads to the disappearance of the free-muon precession signal and the appearance of a large muonium precession signal. Similar results were observed when 0.09% Xe was added to He, as indicated in Table II.

The effectiveness of Reaction (2) encourages the possibility[16] of forming the muonic helium atom $\alpha\mu^- e^-$ by this reaction, involving $\alpha\mu^-$ rather than μ^+, when μ^- are stopped in He with a small admixture of Xe.

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