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Formation of the Muonic Helium Atom, $\alpha\mu^- e^-$, and Observation of Its Larmor Precession*

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The muonic helium atom, $\alpha\mu^- e^-$, has been formed by stopping polarized negative muons in He gas at 14 atm with a Xe admixture of 2%, and observed through its characteristic Larmor precession frequency of 1.4 MHz/G. In addition a nonzero residual polarization of $P = 0.06 \pm 0.01$ for μ^- stopped in pure He gas has been measured for the first time, which corresponds to a depolarization factor of 18 ± 3.

The muonic helium atom $\alpha\mu^- e^-$ is the simple basic atom in which one of the two electrons in a normal helium atom is replaced by a negative muon. In its structure the muonic helium atom is similar to hydrogen with the relatively small muonic helium "nucleus" $(\alpha\mu^-)^+$ corresponding to the proton.[1,2] It is the simplest prototype of an electronic atom with a muonic nucleus[3] and provides an interesting and potentially useful system for study of a very different type of atomic structure, and also for study of the μ^--e^- interaction and for the precise determination of the magnetic moment and mass of the negative muon.

When a negative muon is stopped in He gas, it is captured by a He atom in an Auger process, and then as a result of further Auger and radiative processes will form $(\alpha\mu^-)^+$ in its ground $1S$ state. In a collision with He at thermal energy $(\alpha\mu^-)^+$ cannot capture an electron to form $\alpha\mu^- e^-$ because of the 11.0 eV difference in binding energy of an electron in He and in $\alpha\mu^- e^-$.[4] Hence to form $\alpha\mu^- e^-$ an electron donor with an ionization potential less than that of $\alpha\mu^- e^-$ is needed; xenon is chosen and the reaction will be[2,5]

$$(\alpha\mu^-)^+ + \mathrm{Xe} \rightarrow \alpha\mu^- e^- + \mathrm{Xe}^+ . \qquad (1)$$

The residual polarization of μ^- in $\alpha\mu^-$ $(1S)$ is an essential factor for our experiment. The theory[6] of the depolarization of a negative muon in its capture and cascade to the $1S$ state due to the μ^- spin-orbit interaction predicts a residual polarization $P = 0.17$, when the initial polarization is 1 and a spin-0 nucleus is involved. For C and many other materials, this value of residual polarization has been observed,[7] but in experiments done thus far in liquid helium[8] and in gaseous helium at 50 atm[9] the residual polarizations observed were about $P = 0.01 \pm 0.02$ and $P = 0.035 \pm 0.024$, respectively. If the $\alpha\mu^- e^-$ atom were formed by Reaction (1), the resulting μ^- polarization in a weak external magnetic field would be $\frac{1}{2}$ that of μ^- in $\alpha\mu^-$ because of the hfs interaction in the atom.[10]

The method of our experiment is the classic and usual one for studying the Larmor precession of muonium[11] (1.4 MHz/G) or of free muons[12] (13.6 kHz/G). Our experiment was done at the Space Radiation Effects Laboratory with a 100-MeV/c μ^- beam of polarization 0.65 from their muon channel. A diagram of the apparatus is shown in Fig. 1; all the counters were plastic scintillation counters. The He gas used was produced[13] with an impurity concentration of less than 1 ppm, and during our experiment was circulated over Ti at 750°C to maintain its purity. The Xe used had an impurity content of less than 25 ppm.[14] Three pairs of mutually orthogonal Helmholtz pair coils nulled out the residual laboratory magnetic field, and an additional Helmholtz pair produced a field B of up to 67 G transverse to the spin direction of the incoming muons. The resultant magnetic field was homogeneous to about ±3% over the gas target, and its stability was better than 0.3% as measured with a Rb optical-pumping magnetometer.[15]

A stopping muon (μ_S) was defined by the coincidence-anticoincidence count $S_1S_2S_3S_4\overline{E}_1\overline{E}_2\overline{E}_3$, and with an incident muon beam S_1 of 3×10^5 sec^{-1}, the μ_S rate was about 600 sec^{-1} with 14 atm of He in the target, and with the target evacuated about 150 sec^{-1} or 25% of the full-target rate. Decay electrons were detected as $e_F = E_1E_2\overline{S}_1\overline{S}_2\overline{S}_3$ or $e_D = E_3E_4$. The time intervals between e_F or e_D and μ_S were obtained with time-to-amplitude converters and pulse-height analyzers.

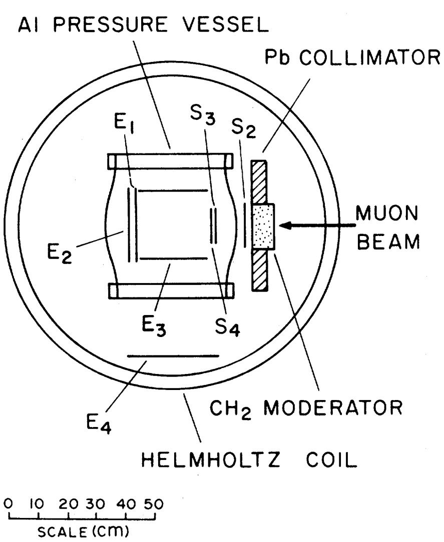

FIG. 1. Vertical cross section of the apparatus. All counters are disks except for E_3 which is a cylinder and E_4 which is square. Not shown is the upstream counter S_1. The counters S_1, S_2, and S_3 were 0.16 cm thick, and S_4 was 0.012 cm thick. The E counters were 0.6 cm thick.

In order to study the residual polarization of μ^- by observation of a free-muon precession signal, data were obtained with pure He at pressures of 7 and 14 atm and in an evacuated target, with $B = 67$ and 4 G. In addition data were taken with Xe admixtures of 0.2 and 1.2%. The time-distribution data were fitted by the equation[16]

$$N(t) = N_0 \exp(-t/\tau) \times [1 + A\exp(-t/\tau_D)\cos(2\pi f t+\varphi)] + B, \quad (2)$$

where $N(t)$ is the observed number of events at time t (an event is an e_F or e_D count occurring at a time interval t after μ_S); N_0 is a normalization constant; τ is the muon lifetime; τ_D is the depolarization time; A is the precession amplitude; f is the precession frequency; φ is the initial phase; and B is a constant background term.

A summary of the results of the data analysis using e_F for the amplitude A_μ at the Larmor frequency for free-muon precession of 0.91 MHz is given in Table I. In pure He at pressures of both 7 and 14 atm a statistically significant signal A_μ was observed; it corresponds to a residual polarization $P \simeq 0.06$, when normalized to an incident μ^- beam with polarization 1. The smaller value of A_μ observed with the target evacuated is consistent with the residual μ^- polarization reported for polystyrene (scintillator); in view of the relatively small number of events associated with target-empty, or wall, μ_S (20% of the full-target event rate) and the large width of the μ^- stopping distribution in grams per square centimeter as compared to the stopping power of the He, the A_μ observed in pure He cannot be due to wall stops. The addition of 1.2% Xe reduced the

TABLE I. Results of data analysis for A_μ at $f = 0.91$ MHz.

Data group	Helium pressure (atm)	Xenon (%)	B (G)	Number of μ_S (10^7)	A_μ (%)
1	14	0	67	3.1	1.24 ± 0.17
2	7	0	67	1.9	1.39 ± 0.24
3	0	0	67	0.9	0.72 ± 0.46
4	14	0.2	67	1.9	1.24 ± 0.22
5	14	1.2	67	2.3	0.25 ± 0.22
6	14	0	4	0.9	−0.34 ± 0.29
7	14	1.2	4	3.0	−0.39 ± 0.18

residual polarization significantly, whereas 0.2% Xe did not. The signal at 0.91 MHz also vanished when the magnetic field was reduced to 4 G.

The observed residual polarization in pure He is smaller by about a factor of 3 compared to the value expected on the basis of the conventional theory of depolarization.[6] The cause of this additional depolarization has not yet been established but is probably associated with collisional Stark mixing of different L levels of $\alpha\mu^-$ during its cascade from high-n states to the $1S$ state.[17] The reduction in A_μ due to the admixture of Xe we interpret as due to the formation of $\alpha\mu^- e^-$ by Reaction (1).

In view of this residual polarization of μ^- in He and its quenching by addition of Xe, data were taken with μ^- to search for the characteristic muonic-helium-atom Larmor precession (the same frequency as that of muonium) in several magnetic fields—3.10, 3.42, 3.73, and 4.64 G—with the stopping gas of He + 2% Xe. An equal amount of data was obtained at each field. Data were also taken under these same conditions with μ^+ stopping in the target to form muonium.[16]

All of the data taken at the four magnetic field values were combined by calculating the amplitude $A(\gamma)$ as a function of the gyromagnetic ratio $\gamma = f/B$, and the result for the e_D spectra is shown in Fig. 2(a). A clear maximum is obtained at $\gamma = 1.4$ MHz/G, which is the characteristic Larmor precession frequency for $\alpha\mu^- e^-$. Its value is $A_{\alpha\mu^- e^-} = (0.53 \pm 0.09)\%$. The width of the resonance is due principally to the inhomogeneity of the magnetic field. Figure 2(b) shows $A(\gamma)$ for a μ^+ run in which the muonium Larmor precession is apparent. The two curves are very similar as is to be expected. The amplitude $A_{\alpha\mu^- e^-}$ is about $\frac{1}{2}$ that of A_μ for μ^- in pure He (Table I), which is also the expected value.

The observation of $\alpha\mu^- e^-$ with the same residual polarization as $\alpha\mu^-$ implies that the $\alpha\mu^- e^-$ atoms are being formed through Reaction (1) in a time short compared to their Larmor precession period. Hence the cross section σ for Reaction (1) at thermal energies is $\sigma \gtrsim 1.5 \times 10^{-17}$ cm^2. This value is consistent with our present knowledge of this cross section.[18]

The formation of polarized muonic helium atoms, $\alpha\mu^- e^-$, should make possible precision measurements of its hyperfine-structure interval $\Delta\nu$ and Zeeman effect similar to those of muonium.[10] The approximate theoretical value for $\Delta\nu$ has been given[1] as $\Delta\nu = 4494.1$ MHz. This value differs from $\Delta\nu$ for muonium[19] ($\Delta\nu_M = 4463.32$ MHz) principally because of the different reduced-mass factors and because of the structure of the $(\alpha\mu^-)^+$ nucleus as compared to the structureless μ^+. Such precision measurements of the muonic helium atom should provide a test of the theory of this atom, and in addition yield precise values for the magnetic moment and mass of the negative muon, for comparison with those of the positive muon as a test of CPT invariance.[20]

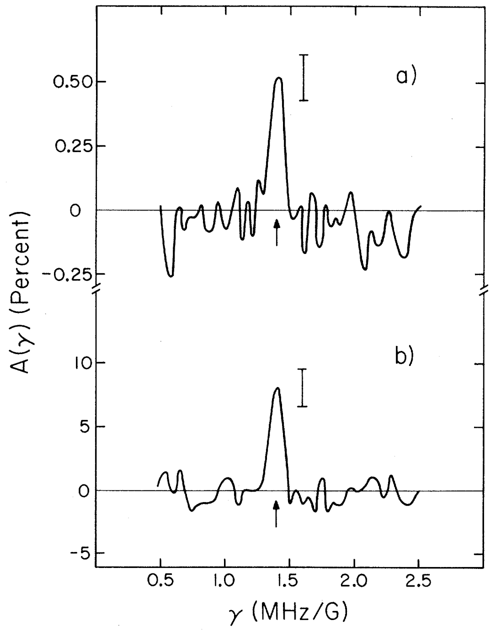

FIG. 2. Observed Larmor precession amplitudes $A(\gamma)$ versus gyromagnetic ratio $\gamma = f/B$: (a) μ^- stopped in He + 2% Xe, and forming $\alpha\mu^- e^-$ (3×10^8 μ_S); (b) μ^+ stopped in He + 2% Xe, and forming $\mu^+ e^-$ (1.8×10^6 μ_S). The arrows indicate the expected gyromagnetic ratio $\gamma = 1.4$ MHz/G.

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Evidence for an Alignment Effect in the Motion of Swift Ion Clusters through Solids*

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Distributions in angle and in energy have been measured for ions transmitted through thin solid targets bombarded by various molecular-ion beams. The results, which differ markedly from those expected from simple Coulomb explosions, indicate that for the ion clusters created inside the target, the internuclear vectors tend to align with the beam direction. An explanation is suggested in terms of a wake potential generated behind each particle as it traverses the solid.

We report on measurements designed to seek evidence for the dynamic interaction between plasma oscillations in a solid and the motions of swift ion clusters. This evidence is sought in deviations from the behavior expected for such clusters undergoing simple Coulomb explosions in solids. We have measured the distributions in angle and in energy of ions transmitted through thin solid targets bombarded by beams of molecular ions. At the energies used (0.15–2.0 MeV per nucleon) one expects the electrons binding a molecule to be torn off within the first one or two