PRODUCTION OF THERMAL MUONIUM IN THE VACUUM BETWEEN THE GRAINS OF FINE SILICA POWDERS

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When spin-polarized positive muons are stopped in fine SiO₂ powder under vacuum, muonium precession is observed indicating 45% muonium formation. Depolarization by oxygen indicates that muonium, like positronium, emerges from the powder grains into the voids.

The recent precision measurement [1] of the vacuum annihilation rate of triplet orthopositronium has emphasized the value of fine powder insulators, such as MgO and SiO₂ [2], in the production of useful amounts of orthopositronium in a vacuum environment. It is thought that positronium is formed in the grains, then diffuses rapidly to the surface and out into the vacuum where it annihilates [3].

Whether positive muons behave similarly in such an environment is of interest, since, for example, the muonium atom, (μ⁺e⁻), may transform into antimuonium, (μ⁻e⁺) [4]. Such a transformation is permitted if the muon number is a parity-like quality rather than an additively conserved quantum quality [5]. Feinberg and Weinberg have shown that such a conversion probability would be greatly reduced by local fields which break the (μ⁺e⁻)–(μ⁻e⁺) degeneracy; such a reduction can be overcome if the (μ⁺e⁻) spends a significant fraction of its life without collisions.

While muonium is known to form in crystalline and fused quartz [6] its formation has hitherto been unobserved in silica powder [7]. We have investigated the production mechanism further, using the stopping π/μ channel at TRIUMF. A spin-polarized beam of 29.8 MeV/c momentum μ⁺, from the decay of pions stopped in the surface of the beryllium pion production target [8], passed through thin Mylar windows and a thin, 0.040 g/cm², beam defining plastic scintillator and then came to rest in a silica powder target. The finest grade of silica powder available to us, bulk density 0.03 g/cm³, radius ~35 × 10⁻⁸ cm, (Cabosil EH5, made by Cabot Corporation, Boston) has been found to give maximum muonium yield. The powder was outgassed and dried at 10⁻⁴ Torr and ultimately held at a pressure of 10⁻⁶ Torr. Provision was made for the introduction of small known concentrations of pure oxygen, a paramagnetic gas which is known to destroy the muonium spin polarization. The thin beam defining counter, 90 cm² in area provided excellent pulse height discrimination against beam positrons while retaining high efficiency (>95%) for muons. Muon stop rates were typically 2 × 10⁴ s⁻¹ per microampere of 500 MeV protons incident on a 10 cm long Be production target. The vacuum vessel was located in an apparatus similar to that described elsewhere [9] in order to monitor the formation and behaviour of muonium atoms by the muonium spin rotation technique [6,9].

Polarized positive muons often form muonium as they stop in a target. In a weak transverse magnetic field, the coherent Larmor precession of the polarized \( F = 1 \) component (50% of the ensemble) is recorded via the asymmetric decay of muons into energetic positrons. The time interval from muon stop to positron detection in a fixed direction is measured and a histogram for many such events is accumulated. This spectrum has the form

\[
N(t) = N_0 e^{-t/\tau_{\mu}} \left( 1 + A_M e^{-\lambda t} \cos(\omega_M t + \phi) + A_\mu \cos(\omega_\mu t - \phi) \right) + B,
\]

(1)
Fig. 1. Muonium precession signals from a silica powder (3.5 nm radius) target at 2.7 G in different oxygen concentrations. Exponential muon decay and random background have been removed to emphasize the fast muonium precession and slow free muon component, which appears almost linear on this time scale.

where $\tau_\mu$ is the mean muon lifetime (2.2 $\mu$s), $A_M$ and $A_\mu$ are the muonium and free muon asymmetries, $\omega_\mu$ is the free muon Larmor precession frequency, $\omega_M(\sim 10^3 \omega_\mu)$ is the muonium frequency, and $\phi$ is an initial phase angle. $N_0$ and $B$ account for normalization the relaxation rate versus oxygen concentration (fig. 2) and random background, respectively, while $\lambda$ is the muonium precession relaxation rate.

Time spectra were obtained for several target environments ranging from vacuum, $< 1.2 \times 10^{14}$ oxygen molecules per cm$^3$, to $4.75 \times 10^{16}$ per cm$^3$. The spectra were fitted to the form (1) using multiparameter chi-squared minimization. The parameters of interest here are the muonium asymmetry ($A_M$) and relaxation rate ($\lambda$).

Fig. 1 shows three asymmetry plots, where the exponential muon decay and random background have been removed to emphasize muonium precession and the free (low frequency) muon precession component. The increase in the muonium relaxation rate with oxygen concentration is apparent, indicating that muonium is being formed and then depolarized by interaction with paramagnetic O$_2$ in the powder interstices. The slope of the 3.5 nm powder data (squares) yields a bimolecular rate constant equal to that obtained with an argon moderator. At large O$_2$ concentration, muonium formed in 3.5 nm powder shows a relaxation rate consistent with this rate constant while in the 7.0 nm powder (triangles) it relaxes much more slowly, independent of oxygen concentration, consistent with a diffusion model. Note that at zero O$_2$ concentration the relaxation rates for 7.0 and 3.5 nm powders are the same. A 7.0 nm point taken at 500 $\times$ 10$^{15}$ cm$^{-3}$ O$_2$ concentration (off the scale of the graph) gave a relaxation rate of $1.44 \pm 0.15$ $\mu$s$^{-1}$ consistent with the line.

Fig. 2. Relaxation of muonium formed in SiO$_2$ powder due to interaction with paramagnetic O$_2$ in the powder interstices. The slope of the 3.5 nm powder data (squares) yields a bimolecular rate constant equal to that obtained with an argon moderator. At large O$_2$ concentration, muonium formed in 3.5 nm powder shows a relaxation rate consistent with this rate constant while in the 7.0 nm powder (triangles) it relaxes much more slowly, independent of oxygen concentration, consistent with a diffusion model. Note that at zero O$_2$ concentration the relaxation rates for 7.0 and 3.5 nm powders are the same. A 7.0 nm point taken at 500 $\times$ 10$^{15}$ cm$^{-3}$ O$_2$ concentration (off the scale of the graph) gave a relaxation rate of $1.44 \pm 0.15$ $\mu$s$^{-1}$ consistent with the line.
with our interpretation this implies that at least 97% of the muonium atoms formed emerge into the voids before the $\mu^+$ decays. By normalizing to the asymmetry $A_M$ in argon gas at 1290 Torr, in which $(64 \pm 16)\%$ of muons injected form muonium [11], we estimate $(45 \pm 20)\%$ muonium formation in this silica powder. This number is in accord with an estimate based on the muon asymmetry observed in copper, in which no muonium is formed, and that observed in the powder with oxygen present. Spectra were taken with larger $70 \times 10^{-8}$ cm radius silica particles, and a comparatively small relaxation rate (i.e. a long-lived muonium precession signal) was measured at high $O_2$ concentration (fig. 2). This presumably is due to $(\mu^+e^-)$ atoms that remain inside the grains, where they are not depolarized. If we assume that complete depolarization occurs the instant the muonium atom emerges from the particle surface (valid for high oxygen concentrations), a calculation, similar to that in ref. [2] for positronium diffusion, shows that the time dependence of the muonium asymmetry should not be $A(t) = A_M e^{-\lambda t}$ as in eq. (1), but rather

$$A'(t) = A_M \left\{ \text{erf}[\gamma t] - \frac{3\pi^{-1/2}}{2} (\gamma t)^{1/2} \right\}$$

where $\beta = D/R^2$, $D$ is the diffusion constant, and $R$ is the particle radius. Fitting the asymmetry time dependence with eq. (2) allows us to extract $D$ from high-concentration data for both powder particle sizes. From the horizontal line in fig. 2, the $70 \times 10^{-8}$ cm powder sample, $D = (2.2 \pm 0.4) \times 10^{-7}$ cm$^2$ s$^{-1}$.

From the highest oxygen concentration point for the $35 \times 10^{-8}$ cm sample, $D = (4.5 \pm 1.1) \times 10^{-7}$ cm$^2$ s$^{-1}$, but the relaxation is so fast that fitting the time dependence of $A'(t)$ is difficult even with good statistics. For comparison, the value for the positronium diffusion constant is $D = (5.8 \times 1.9) \times 10^{-5}$ cm$^2$ s$^{-1}$ at room temperature [2], using this model.

Preliminary investigations of $Al_2O_3$ and $ZnO$ powders showed these to be much less promising for the production of muonium in the voids.

References