Formation of muonium in condensed neon

E. P. Krasnoperov, E. E. Meĭlikhov, A. N. Ponomarev, and
V. Yu. Pomyakushin
Kurchatov Institute Russian Science Center, 123182 Moscow, Russia

D. G. Eshchenko
Institute of Nuclear Research, Russian Academy of Sciences, 117334 Moscow, Russia

V. N. Duginov, V. A. Zhukov, T. N. Mamedov, and V. G. Olshevskiĭ
Joint Institute for Nuclear Research, 141980 Dubna, Moscow Region, Russia

(Submitted 5 May 1994)
Pis'ma Zh. Eksp. Teor. Fiz. **59**, No. 11, 721–724 (10 June 1994)

Muon polarization in condensed neon has been studied as a function of the electric and transverse magnetic fields. In solid neon, more than 80% of the muonium forms in a time of less than 1 ns, while in the liquid phase the observed muonium fraction in a transverse field of 8 G is 20%. The muonium formation time in the crystalline phase is short in comparison with that in the liquid phase because of the high mobility of excess electrons.

The formation of muonium in condensed inert gases is an interesting problem which is still far from complete resolution. The existing models[1,2] do not provide a quantitative explanation of the observed diamagnetic and paramagnetic fractions or their evolution with the temperature, in particular, in the course of phase transitions.[3] A case of particular interest is liquid helium, in which the muonium forms[4,5] in the course of a recombination of a muon and an electron at a distance $\simeq 5\times 10^{-5}$ cm, which corresponds to an attractive field $E\simeq 200$ V/cm. The time taken for the particles to move close to each other depends on scattering by excitations, and is shorter, the higher the mutual mobility: $\tau \propto 1/b$. The increase in the mobility of charges during the cooling of superfluid helium means that an external electric field can be used to observe the kinetics of the formation of muonium over a broad time interval and to effectively act on this kinetics.[4,5]

The mobility of electrons in neon increases in the course of crystallization, from $b=0.0016$ cm^2/(V·s) (in the liquid) to 600 cm^2/(V·s) (in the solid).[6] The excess electron becomes delocalized in solid neon, going into the conduction band.[7] In a liquid, conditions are more favorable for the formation of a "bubble" about 7 Å in radius around an electron. This bubble has a low mobility, as in normal helium, by virtue of the Stokes viscosity. On the other hand, the cross section for the charge exchange of a muon in neon at energies below 100 eV is apparently extremely small, while the cross section for the loss of an electron by muonium is still significant. Accordingly, the muonium fraction in gaseous neon is less than 3% (Ref. 8). It would be interesting to study the kinetics of muonium formation in neon in the course of a phase transition in which the mobility changes by several orders of magnitude. It would also be interesting to compare how the mass of the atoms of the medium affects the characteristic separation of the electron–muon pair in comparison with that in liquid helium.

The muon experiments were carried out at the phasotron of the JINR in the standard arrangement.[9] The sample chamber was a complete brass cylinder 80 mm in diameter sealed with bronze foil 0.1 mm thick. A thin copper electrode was placed in the chamber to create an electric field. The sample thickness was 2 cm. The chamber was placed in a standard flow-through cryostat[10] and cooled by an adjustable flow of helium. The gaseous neon was subjected to double cryogenic purification. The amount of the "dangerous" impurity—paramagnetic oxygen—was less than 0.01%.

The muonium component of the precession spectrum was measured in liquid neon ($T=26$ K) and solid neon ($T=23$ K) in a transverse magnetic field of 8 G. Allowing for the 10–15% of the muons stopped in the intermediate walls of the chamber and the cryostat, we find that the muonium fraction in solid neon is $F_{\mathrm{Mu}}=80\pm5\%$, while the muon fraction is $F_{\mu}\simeq20\%$. When the neon melts, the paramagnetic (muonium) fraction decreases sharply to $F_{\mathrm{Mu}}\simeq20\%$, while the diamagnetic fraction naturally increases, reaching $F_{\mu}\simeq70\%$. The missing 10%, usually called the "lost fraction," is associated with a slowing of the formation of muonium. We show below that this fraction is manifested in an external electric field.

The formation of the muonium, stretched out over a time τ, has the consequence that the precession amplitude decreases with increasing magnetic field, because of phase coherence at[2,4] $\omega_{\mathrm{Mu}}\tau\simeq1$. In solid neon, the muonium asymmetry decreases by about 20% as the transverse magnetic field is raised from 8 to 50 Oe. In this approximation we allowed for the hyperfine splitting, which is 4490 ± 40 MHz. If we assume that the decrease in A_{Mu} is due to the kinetics of the closing of the muon and the electron on each other, then we can estimate the time scale for the formation of muonium: no greater than $\tau\simeq1$ ns.

The validity of some model or other for the formation of muonium can be evaluated from the effect of an external electric field. At a hot wall[1] or in the course of radiolysis,[2] the fields achievable experimentally at atomic distances cannot affect the formation of muonium. If the governing effect is instead the kinetics of the closing of the muon and the electron to within a distance $\geqslant10^{-6}$ cm, then the electric field radically affects the muonium formation probability.[4] Figure 1 shows the behavior of A_{Mu} in condensed neon during the application of a voltage to the electrode. In the crystalline phase, the asymmetry of the muonium decreases with increasing field, but the branches of the curve are asymmetric: The positive potential causes a faster decrease in A_{Mu} than the negative potential does. The asymmetry of $A_{\mathrm{Mu}}(E)$ is due to the anisotropic distribution of electron–muon pairs. As is clear from the experimental geometry (see the inset in Fig. 1), the muon density is shifted forward along the beam with respect to the electron density. The typical electric fields required to suppress muonium formation are about an order of magnitude stronger than in helium.[4] The separation of electron–muon pairs is correspondingly smaller.

The lines in this figure are calculated amplitudes of the muonium precession for solid neon. It was assumed that the muon and the electron approach each other under the influence of the Coulomb force. We considered the motion of the electron alone, since its mobility is several orders of magnitude higher than that of a positive charge.[6] The electron motion is "viscous" (the velocity is along the same direction as the force), for the following reasons. The typical distance between an electron and a muon, determined from the decrease in A_{Mu} in a field (Fig. 1), is $R\sim\sqrt{e/E}\sim10^{-5}$ cm. This figure is small in comparison with the Onsager length $r_c=e^2/\varepsilon kT\approx6\times10^{-5}$ cm (ε is the permittivity),

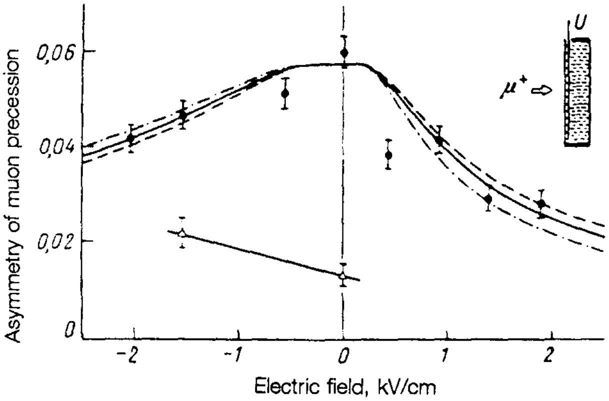

FIG. 1. Muonium asymmetry in solid neon (●; $T=23$ K) and liquid neon (△; $T=26$ K) versus the external electric field. The solid curve was calculated for a model for distribution with $R_m=0.38\times10^{-5}$ cm and $\Delta=0.96\times10^{-5}$ cm. The dashed curve shows the behavior for $R_m=0.3\times10^{-5}$ cm and the same value of Δ. The dot-dashed curve corresponds to $R_m=0.5\times10^{-5}$ cm.

beyond which the motion is diffusive. The relaxation time of the electron velocity in the electric field is $\tau_{\rm rel}\simeq m_e b/e$, where m_e is the electron mass, and $b=600$ cm^2/(V·s) is the mobility of the electron in solid neon. This mobility is also smaller in comparison with the particle closing time. Taking the nonlinearity of the velocity $v(E)$ into account, we find the following expression[6] for this time:

$$\tau=\int_R^0\frac{dr}{v(r)}\approx0.37\sqrt{\frac{\varepsilon}{bue}}R^2\simeq10^{-10}\ \text{s},$$

where $u=10^5$ cm/s is the sound velocity in solid neon.

It can be shown that if an electron is moving along a line of force then the trajectories whose initial coordinates satisfy

$$r<\sqrt{\frac{e}{\varepsilon E}}\,\frac{1}{\cos(\vartheta/2)}\tag{1}$$

(ϑ is the angle between the radius vector $\mathbf{r}$ connecting the particles and the external electric field $\mathbf{E}$), terminate at the center (at the μ^+), while the other trajectories run off to infinity. The meaning here is that an electron recombines with a muon only inside trajectory (1). Specifying the initial radial distribution of electrons with respect to the muons by a Gaussian function

$$p(\mathbf{r})=A\pi^{-3/2}\Delta^{-3}\exp\left[-\left(\frac{\mathbf{r}-\mathbf{R}_m}{\Delta}\right)^2\right],$$

we can easily calculate the probability for recombination, as the integral of (2) over the volume inside trajectory (1). Theoretical curves of $A_{\rm Mu}(E)$ are plotted in Fig. 1. The best approximation is a distribution with the parameter values $\Delta=(1.0\pm0.1)\times10^{-5}$ cm, $R_m=(0.4\pm0.1)\times10^{-5}$ cm, and $A=0.77\pm0.03$.

The value of A_{Mu} at $E=0$ is $\simeq 0.8$ of the maximum possible value. The reasons for this incomplete formation of muonium may be either instrumental or physical. An effect of intermediate layers on A_{Mu} in the case of ordinary muon beams ($p=125$ MeV/c) was discussed above. Another reason may be that the electron density distribution is more gently sloping than a Gaussian distribution, so some of the particles lie outside the Onsager sphere. However, incorporating such particles has little effect on the values of R_m and Δ, especially since they are considerably smaller than the distribution parameters $R_m \simeq 4.5\times 10^{-5}$ cm and $\Delta \simeq 3.5\times 10^{-5}$ cm in liquid helium.[11]

The anisotropy of the distribution of $\mu^+ - e^-$ pairs is also manifested in liquid neon, in which the charge mobility is low, and only a small fraction of the muons recombine into muonium during the observation time. In this case, as can be seen from Fig. 1, the asymmetry of the muonium increases when the external field is directed along the Coulomb attraction field. A large negative field eliminates the "lost fraction," since, combining with the Coulomb field, it reduces the time scale of the closing of the muon and the electron, τ. The dephasing effect shifts toward stronger magnetic fields, and the observable value of A_{Mu} correspondingly increases.

In condensed neon, as in helium, the muonium formation kinetics is thus governed by the mobility of the charges. The muon–electron spatial distribution in the course of the thermalization is anisotropic (the muon density is shifted ahead along the direction of the beam momentum). The characteristic field of the interaction of the particles of the pair is $\simeq 1$ kV/cm. This mechanism for the formation of muonium apparently also operates in other condensed inert gases with a high mobility of excess charges. Further research will be required to clarify just how general this phenomenon is and to clarify the reasons for the large electron–muon separation distances (more precisely, for the small value of the electrostatic attraction of the muon toward the electron) and the anisotropy of their distribution.

We wish to thank V. G. Grebinnik, A. F. Burtsev, K. I. Gritsaĭ, and I. A. Krivosheev for invaluable technical assistance. This study was carried out as part of Project 93-02-02587, financed by the Russian Basic Research Foundation, and with the support of O. V. Savchenko, who maintained the operation of the phasotron during the muon studies.

[1] D. C. Walker, *Muon and Muonium Chemistry* (Cambridge Univ. Press, Oxford, 1983).

[2] P. W. Percival *et al.*, Chem. Phys. **32**, 353 (1978).

[3] R. F. Kiefl *et al.*, J. Chem. Phys. **78**, 308 (1981).

[4] K. Krasnoperov *et al.*, Phys. Rev. Lett. **69**, 1560 (1992).

[5] R. Abela *et al.*, JETP Lett. **57**, 157 (1993).

[6] R. Balzer *et al.*, Phys. Rev. B **4**, 3636 (1971).

[7] W. E. Spear and P. G. LeComber, in *Rare Gas Solids*, ed. by M. L. Klein and J. A. Venables (Academic, New York, 1977), Vol. 2.

[8] M. Senba, J. Phys. B **22**, 2027 (1989).

[9] I. I. Gurevich and B. N. Nikol'ski, *Experiments on the Physics of Positive Muons* [in Russian] (IAE, Moscow, 1976).

[10] V. G. Grebinnik *et al.*, JINR Reports, R13-83-20 (1983).

[11] E. P. Krasnoperov *et al.*, to be published in Hyper. Int., 1994.

Translated by D. Parsons