TEMPERATURE AND DENSITY DEPENDENCE OF THE LOCAL MAGNETIC FIELD IN DENSE XENON GAS*

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We report precise NMR frequency measurements on fluid xenon which show a temperature-dependent local magnetic field and small but significant deviations from a linear density dependence of the local field. These data can be used to obtain values for the shift of the local field from its zero-density limit as well as the temperature dependence of the shift per unit density in the low-density limit.

Previous NMR frequency measurements[1-3] of the local magnetic field H in gaseous xenon can, with the given limits of the experimental errors, be described best by a linear dependence of the field on density at constant temperature. As a result, calculations of the low-density limit of the local field shift per unit density[4-6] have been compared with the linear extrapolation of the higher density measurements to low density. Moreover, with these error limits, no experimental evidence for temperature dependence of the local field at constant density has been detected.

The shift ΔH of the local magnetic field in fluid xenon[7,8] in an external field H_0 is paramagnetic: $\Delta H = H - H_{\rho=0} > 0$. The local field in the limit of zero density, $H_{\rho=0}$, is slightly smaller than H_0 because of electron diamagnetism. The average shift is given by a statistical average[4] over the radial distribution function $g(R, \rho, T)$:

$$\frac{\langle \Delta H(\rho, T)\rangle}{H_0} \equiv \langle \sigma(\rho, T)\rangle = 4\pi\rho \int_0^\infty \sigma(R) g(R, \rho, T) R^2 dR.$$

Here ρ is the sample density, $\langle\sigma(\rho, T)\rangle$ is the average shift (or paramagnetic shielding) per unit applied field, and $\sigma(R)$ is the paramagnetic field per unit applied field occurring at one nucleus in the presence of a second nucleus a distance R away. Adrian[5] has shown that $\sigma(R)$ is almost exclusively determined by the short-range exchange interactions between electrons on the two colliding atoms. His calculated expression for $\sigma(R)$ can be fitted in the region of interest by a rapidly decreasing exponential with a characteristic range of about one-tenth the hard-core radius R_0. As a result, the average shift is dominantly determined by the behavior of $g(R, \rho, T)$ in the region $0.9R_0 < R < 1.3R_0$.

The radial distribution function for a dilute gas is the Boltzmann factor, $\exp[-U(R)/kT]$, where $U(R)$ is the two-body interaction potential. Using a modified Buckingham (6-exp) potential, Adrian made a calculation of the shift per unit density. His value at room temperature was

$$\langle\sigma\rangle = 2.8\times10^{-7}\rho,$$

where ρ is in amagat units (1 amagat = density at 0°C and 1 atm pressure). Another result of his calculation was the prediction of a small temperature dependence with a minimum in the shift at constant density at about 300°C. More recently, Lurie[6] and Horton and Lurie,[9] in a separate calculation of the low-density shift and using a potential by Munn and Smith,[10] have obtained $\langle\sigma\rangle = 4.4\times10^{-7}\rho$ with the temperature minimum at about 400°C.

We have now observed small but important deviations from a linear density dependence for the local field at constant temperature. This is shown in Fig. 1 for 20 and 80°C. We have also

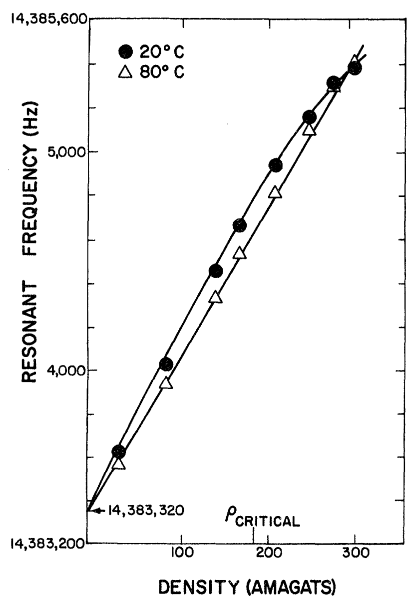

FIG. 1. The Xe^{129} free-precession frequency (which is directly proportional to the local field H) as a function of xenon density at two temperatures in a field of 12.2 kG. Errors are smaller than size of points shown.

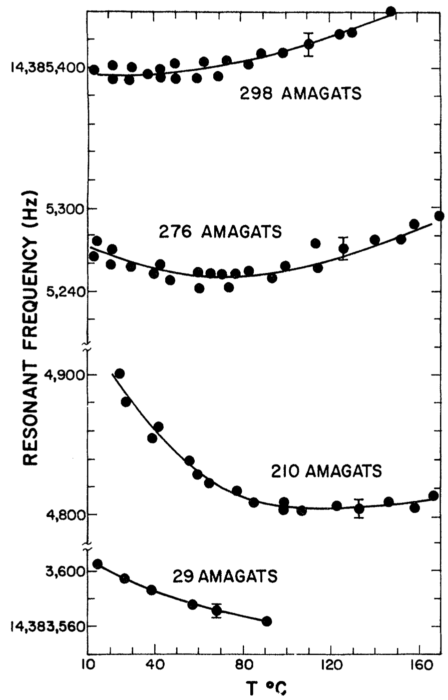

FIG. 2. The Xe^{129} free-precession frequency as a function of temperature for xenon at four densities. Note the two breaks on the vertical scale. Errors shown are typical of all points on curve.

observed the temperature variation at constant density and have observed minima for high-density samples; Fig. 2 shows the temperature dependence of four of our eight samples. These minima are density dependent and occur at lower temperatures than predicted by Adrian or Horton and Lurie for low densities; the behavior of the data from all samples is consistent with a shifting of the minimum to lower temperatures at high densities.

The observed local field H can be fitted well using the quadratic form

$$H/H_0 = A(T) + B(T)\rho + C(T)\rho^2,$$

where $A(T)H_0 = H_{\rho=0}$ and is a constant for all temperatures. Fitting at 20, 40, 60, and 80°C we obtain, respectively, $B(T) = (6.1, 5.4, 5.1, 4.9) \times 10^{-7}$ amagat^{-1} (all $\pm 0.2\times 10^{-7}$), $C(T) = (-4.7, -2.6, -1.3, -0.6)\times 10^{-10}$ amagat^{-2} ($\pm 1.1\times 10^{-10}$). Using these fitted equations we plot

$$\frac{\langle\sigma(\rho, T)\rangle}{\rho} = \frac{H - H_{\rho=0}}{\rho H_0} = B(T) + C(T)\rho$$

in Fig. 3. One result of this fit is a more accurate estimate of the low-density limit of $\langle\sigma\rangle/\rho$. This is of special interest since the theoretical calculations in the absence of accurate radial

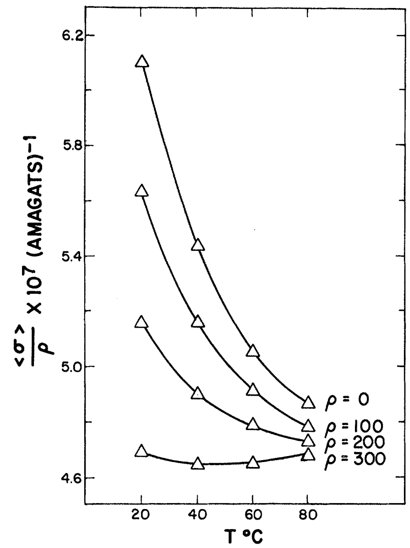

FIG. 3. The Xe^{129} shift per unit density at four densities as calculated from our fitted curves.

distribution functions at high densities are best done in the limit of low densities. But according to our results a linear extrapolation to low density is incorrect. Our new value for $H_{\rho=0}$, based on the quadratic extrapolation, is lower (ΔH, higher) than previously thought. In the low-density limit at 20°C we obtain

$$(\langle\sigma\rangle/\rho)_{\rho=0} = (6.1 \pm 0.2)\times 10^{-7} \text{ amagat}^{-1}.$$

This compares with the value

$$\langle\sigma\rangle/\rho = 4.6\times 10^{-7} \text{ amagat}^{-1},$$

which is the previously quoted value[2,3] and is based on the slope of the previous gas measurements. This, however, does not mean that the previous data are inaccurate—they simply are less precise, allowing only a linear rather than a quadratic fit. Making a linear fit to our data we also obtain

$$\langle\sigma\rangle/\rho = 4.6\times 10^{-7} \text{ amagat}^{-1},$$

but we see systematic curvature and obtain a much better fit by including the second-order term. An attempt to include a cubic term, however, leads to no better fit. Another indication of our improved value is that the fitted value of $H_{\rho=0}$ is the same within our errors for all four temperatures.

We point out that the temperature and density dependence of the shift can be explained qualitatively in terms of the calculated temperature and density dependence of the radial distribution function near the hard-core region for low- and moderate-density gas,[11] and we foresee applications of this experiment to studies of the radial distribution function in this region ($0.9R_0$ to $1.3R_0$) for fluid xenon at all densities.

In the present measurements[12,13] the local magnetic field was measured by NMR free-precession techniques at a field of 12.2 kG in which the resonant frequency of Xe^{129} was measured in constant applied field H_0. Improved field stability, more stable frequency sources, and the use of signal averaging techniques resulted in the greater precision of these measurements.

The samples were similar to those used in previous investigations,[2,7] consisting of sealed Pyrex containers of (constant) volume about 0.2 cm^3. Densities were determined by weighing and are known to 1%. Higher temperature (pressure) measurements were obtained in this work by keeping the Pyrex containers under pressure in a BeCu pressure vessel to compensate for internal gas pressures. Some of the measurements at lower densities were performed in a 7-kG permanent magnet. The excellent stability of this magnet (drift <1 part in 3×10^8 per min) kept the resonant frequency constant, allowing the signal averager to be used to better advantage. Because of the smaller magnet gap, our pressure vessel could not be used in this magnet; this limited the study to the lower densities at temperatures up to 90°C. The measurements on the 29-amagat sample which were made in this magnet at 7 kG have been scaled to 12.2 kG for presentation on Fig. 2.

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ANOMALOUS RESISTIVITY IN COLLISIONLESS PLASMA SHOCK WAVES*

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The anomalously large resistivity observed in collisionless shock-wave experiments is explained in terms of a drift instability of ion acoustic waves.

A number of experiments[1,2] have detected shock waves traveling perpendicular to an ambient magnetic field $\vec{B}=B_0\hat{n}_z$ and established that the structure of these waves implied a resistivity in the shock front much larger than the resistivity due to electron-ion collisions. This anomalous resistivity was made evident by the width of the shock front, L_s, which far exceeded the classical width.[3]

A model for explaining this enhanced width in terms of ion waves driven unstable by currents in the shock front has been proposed by Sagdeev. Early calculations[4] based on this model produced results which were too large by two orders of magnitude to agree with the experimental resistivity. However, when the results were multiplied by an arbitary factor $A\approx0.01$ they did give a shock thickness which scaled with density in