Noble-Gas NMR Detection through Noble-Gas–Rubidium Hyperfine Contact Interaction

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Enhanced noble-gas NMR signals are observed in mixed noble-gas–rubidium samples by monitoring spin polarization of the optically pumped rubidium ensemble mechanized as a magnetometer. These signals are believed to arise through electron exchange enhancement of the contact hyperfine interaction during noble-gas–rubidium binary collisions. Polarization of the noble-gas magnetization is obtained through spin exchange with the rubidium ensemble.

The use of optically pumped Rb vapor to transfer polarization to a second atomic species through spin-exchange collisions is well known[1] and was first used to polarize a noble gas (NG) by Bouchiat, Carver, and Varnum[2] in their work with ^{3}He. The method has been extended in this laboratory to include all the stable NG isotopes.

Several methods have been used for the detection of NG nuclear magnetism polarized through spin exchange with Rb: measurement of the induced voltage in rf detection coils in a NMR experiment in the case[2,3] of ^{3}He and also in the case[4] of ^{120}Xe, and direct observation of the magnetic dipole field of the oriented nuclei by an adjacent ^{87}Rb magnetometer.[5] For my detection scheme, I also use a Rb magnetometer mechanized in the zero-field level-crossing mode[6]; however, here the Rb atoms within the mixed Rb-NG sample cell comprise the magnetometer sensor. By this method I have successfully observed enhancement of the nuclear polarization in the NG isotopes ^{3}He, ^{21}Ne, ^{83}Kr, ^{129}Xe, and ^{131}Xe.

The experimental setup consists of a 15-ml Pyrex sphere filled with Rb metal, a buffer gas of ^{4}He at 500 Torr, and one or more species of NG at a pressure on the order of 1 Torr. The cell is contained within a resistance-heated oven provided with Pyrex windows at either end. The oven is capable of controlled temperatures to 85°C. A three-axis set of Helmholtz coils surrounds the oven, and the whole assembly is placed within a cylindrical magnetic shield which reduces external magnetic fields to below 10 μG. The Rb atoms are optically pumped in the classical fashion[1,3] with circularly polarized D_1 resonance radiation from a Rb lamp placed at one end of the shield. The light is directed along the shield axis (x axis) and the transmitted light is collected by a photodetector.

The Rb ensemble is mechanized as a magnetometer by applying a rf field, $H_1 \cos\omega t$, along the z axis ($\omega/2\pi = 8$ kHz). The light transmitted by the resonance cell, measured by a photocell, is modulated at various harmonics $p\omega$ of ω. The modulation component for which $p = 1$ is proportional to the z-axis field and is insensitive to first order to the other components.[6] In order to measure the NG magnetization, it is oriented along the magnetometer sensitive z axis in the following fashion. A small magnetic field H_y (100 μG) is applied at right angles to a larger field H_x (2 mG) that is parallel to the pumping light. After a time sufficient to allow a buildup in NG polarization, the field H_x is reduced to zero in a time sufficiently short to allow the full NG magnetization that has been established along H_x to precess coherently about H_y with a sinusoidal component along the z axis. These signals are calibrated in magnetic field units by applying a known test current through the z-axis Helmholtz-coil pair surrounding the sample. In this fashion, the NG magnetization and its exponential growth and decay constants can be measured, and the influence of exchange collisions and relaxation mechanisms operating within the cell can be studied.

The expected NG nuclear polarization P_{NG} can be expressed in terms of the equilibrium electronic polarization P_{Rb} produced by optically pumping the Rb vapor, the Rb-NG spin-exchange time T_{ex}, and the NG nuclear longitudinal relaxation time[7] T_1:

$$P_{NG} = T_p P_{Rb}/T_{ex}, \tag{1}$$

where $T_{ex} = (\sigma_{ex}\bar{v}N_{Rb})^{-1}$, σ_{ex} is the NG-Rb spin-exchange cross section, $\bar{v}$ is the average relative velocity, and N_{Rb} is the rubidium atomic density.[8] The time characterizing the NG polarization growth is $T_p = (1/T_{ex} + 1/T_1)^{-1}$.

First-order estimates of the time constants T_1 and T_{ex} for ^{129}Xe were obtained by fitting the measured values of T_p to a model where T_1 and T_{ex} are assumed constant with temperature over the range 54°C to 85°C and $T_{ex} = (\sigma_{ex}\bar{v}N_{Rb})^{-1}$ using

values for N_{Rb} from the literature.[9] ^{129}Xe data were taken using 15-ml samples containing 0.5 Torr Xe (65% ^{129}Xe enriched), a buffer gas of 500 Torr ^{4}He, and either ^{87}Rb or ^{85}Rb. With the model assumed, the intercepts of Fig. 1 give a longitudinal relaxation time $T_1 = 24 \pm 1$ min, while the slopes indicate a probable dependence on the Rb isotope used: $\sigma_{ex}(^{87}\text{Rb}) = (1.9 \pm 5\%) \times 10^{-19}$ cm^2, $\sigma_{ex}(^{85}\text{Rb}) = (1.5 \pm 5\%) \times 10^{-19}$ cm^2.

In the classical formulation, this Rb magnetometer would sense the internal field arising from the nuclear spins. The field is uniform over the cell volume and has a value

$$\Delta H = 8\pi M_{NG}/3, \qquad (2)$$

where M_{NG} is the NG magnetization, $M_{NG} = \mu NP$, μ is the nuclear magnetic moment, N is the density, and P is the fractional polarization of the NG species. The Rb magnetometer signals arising from ^{129}Xe at 62°C are equivalent to a field of 4.3×10^{-5} G. This is 3 orders of magnitude larger than the expected value of $\Delta H = 4.2 \times 10^{-8}$ G obtained using Eqs. (1) and (2) with P_{Rb} estimated to be no greater than 10%, $T_p = 8.8$ min, $T_{ex} = 12.6$ min, $P_{Xe} = 10\%$.

Similar enhancement was observed with ^{83}Kr. Samples with 10 Torr Kr (72% ^{83}Kr enriched) are characterized by pumping times as long as 15 min with little temperature dependence. It is estimated that the exchange time for ^{83}Kr with Rb is in excess of 200 minutes at 62°C with a resulting ^{83}Kr polarization of less than 1%. The internal field by Eq. (2) is less than 10^{-7} G. The measured Rb magnetometer signals from ^{83}Kr are equivalent to a field of 8×10^{-6} G, or at least 2 orders of magnitude larger than permitted by the classical formulation.

A preliminary explanation of these anomalously large signals (compared to those given by a classical dipole average field) has been developed on the basis that the Rb magnetometer signals arise from the individual NG magnetic moments through the contact hyperfine interaction between the alkali atom and the noble-gas atom during a binary collision, as discussed by Herman[10] and by Gamblin and Carver.[3] The final results of this work will be published.

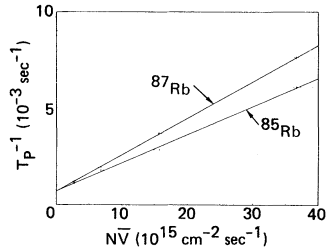

FIG. 1. Least-squares linear fit of ^{129}Xe T_p^{-1} vs product $N\bar{v}$ of Rb density and relative velocity for ^{85}Rb and ^{87}Rb samples. Vertical error bars were obtained from a three-parameter fit of the measured exponential growth of the ^{129}Xe signal vs time. Horizontal error bars indicate a ± 1°C uncertainty in temperature.

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[1]See, for example, W. Happer, Rev. Mod. Phys. 44, 169 (1972).

[2]M. A. Bouchiat, T. R. Carver, and C. M. Varnum, Phys. Rev. Lett. 5, 373 (1960).

[3]R. L. Gamblin and T. R. Carver, Phys. Rev. 138, A946 (1965).

[4]E. Kanegsberg, unpublished.

[5]C. Cohen-Tannoudji, J. DuPont-Roc, S. Haroche, and F. Laloë, Phys. Rev. Lett. 22, 758 (1969).

[6]C. Cohen-Tannoudji, J. DuPont-Roc, S. Haroche, and F. Laloë, Rev. Phys. Appl. 5, 95 (1970).

[7]W. A. Fitsimmons, L. L. Tankersley, and G. K. Walters, Phys. Rev. 179, A156 (1969).

[8]Polarization refers to the fractional population difference of a two-level spin-$\frac{1}{2}$ representation of the atom.

[9]*Metals Reference Book*, edited by Colin G. Smithells (Butterworth, Washington, D. C., 1962), 3rd ed., p. 655.

[10]R. M. Herman, Phys. Rev. 137, A1062 (1965).