Systematic Pseudomagnetic Measurements of the Spin-Dependent Scattering Length of Slow Neutrons with Atomic Nuclei

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The magnitude and the sign of spin-dependent scattering lengths of slow neutrons by nuclei of Li^7, Al^{27}, Sc^{45}, Zr^{91}, Nb^{93}, La^{139}, and Ta^{181} have been determined by measuring the dependence of the precession angle of the neutron spins on the nuclear polarization of the scattering target.

The scattering of slow neutrons by a fixed nucleus can be described by the scattering length

$$A_N = a_0 + a_N \vec{I}_N \cdot \vec{s},$$

where $\vec{I}_N$ and $\vec{s}$ are the spins of the nucleus and the neutron, respectively. The parameter $a_N = (a_+ - a_-)/(I_N + \frac{1}{2})$ (a_+ and a_- being the nuclear scattering lengths of the nucleus for the two spin channels $I_N + \frac{1}{2}$ and $I_N - \frac{1}{2}$) is unknown for most nuclei. The growing use of polarized neutron beams, and targets with sizable polarizations obtained either in static fields at very low temperatures or by dynamic nuclear polarization, makes the knowledge of a_N of greater interest. In this Letter, we report values of a_N for a few nuclei.

In analogy to neutron magnetic scattering, a new formalism has been introduced previously, and its physical validity experimentally demonstrated.[1-3] It defines, inside a nuclear target, a pseudomagnetic field H^* produced by the pseudomagnetic moments μ^* of the target nuclei such that

$$H^* = 4\pi M^* = 4\pi N \mu^* P,$$

where N is the number of nuclei per unit volume, P is their polarization, and μ^* is given by

$$\mu^*/\mu_B = -a_N I_N / g_n r_0 = 1.855 \times 10^{12} I_N a_N$$
$$= 1.855 \times 10^{12} [I_N/(I_N + \tfrac{1}{2})](a_+ - a_-),$$

with μ_B the Bohr magneton, $r_0 = e^2/mc^2$ the classical radius of the electron, and $g_n = \mu_n/\mu_N = -1.913$ the neutron magnetic moment expressed in nuclear magnetons. In a static field H_0, the neutron magnetic moment will precess with the Larmor frequency $\omega_L = -\gamma_n H_0$, where $\gamma_n = 2\mu_n/\hbar = -2\pi \times 2917$ sec^{-1} G^{-1} is the gyromagnetic factor of the neutron. The effect of the pseudomagnetic field H^* is to change the Larmor precession frequency ω_L of the neutrons inside the target by an amount $\Delta\omega_L = -\gamma_n H^*$, as first shown theoretically by Barytchevski and Podgoretzki.[4] A very sensitive method to measure small changes in precession frequency is through the change in the precession angle of the neutron polarization. Such a method has been described in a previous Letter.[5] The extra precession angle due to the pseudomagnetic field is $\alpha = -\gamma_n H^* t = -\gamma_n H^* l/v$, l being the sample length and v the neutron velocity. This extra precession angle is measured from the ratio $R = I^+/I^-$ by the relation

$$\cos\alpha = (1 - R)/Dp^2(1 - eR),$$

where I^+ and I^- are the counting rates of the analyzer for opposite incoming-neutron polarizations (corrected for background), p^2 is the product of the polarizing and analyzing efficiencies, and e is the efficiency of the flipping coil used to reverse the incoming-neutron polarization. In our setup, $p^2 = 0.990$ and $p^2 e = 0.981$. The coefficient D takes into account any dephasing process resulting in a decrease of the measured polarization. It has been measured separately for each sample.

The large pseudomagnetic moments of H^1 and V^{51} give measurable precession angles even at 1 K.[5] But for many nuclei, μ^* is much smaller and, consequently, much higher polarizations are needed. Two somewhat complementary methods can be used to achieve sizable nuclear polarizations. The first consists in lowering the temperature of the sample down to the millikelvin region. The second uses microwave techniques to polarize the nuclei dynamically.

In the first method, the main problem is to achieve equilibrium through thermal contact between sample and coolant, and, inside the sample, between the lattice and the nuclear spins. The former is generally good down to, at least, 80 mK, while the latter is satisfactory for metals down to very low temperatures (the spin-lattice relaxation time $\tau \sim 1/T$) and almost nonexistent

at these temperatures for most insulators ($\tau \sim e^{a/T}$).

The second method is able to cool the nuclei far below the lattice temperature. Therefore, it calls for substances with weak spin-lattice coupling, i.e., insulators. It has the advantage that it may be possible to polarize selectively and thus to sort out the contribution of different isotopes in samples with several nuclear-spin species. A disadvantage is the difficulty of measuring the polarization accurately.

Whatever the polarization method, a plot of α against nuclear polarization P is a straight line, whose slope gives μ^*. For static nuclear polarization, P is generally small, and

$$\alpha \cong \xi\left(\frac{I+1}{3I}\right)\left(\frac{\mu^*}{\mu_B}\right)\left(\frac{\mu}{\mu_N}\right)\frac{ldc}{A}\frac{1}{T}, \qquad (1)$$

where μ is the magnetic moment of the nucleus, μ_B and μ_N are the electronic and the nuclear Bohr magneton, respectively, d is the density and A the atomic weight of the element, and c is the abundance of the isotope with spin I. ξ is defined by

$$\xi = -\frac{H}{v}\,4\pi\gamma_n\frac{(\mu_B N_0)^2}{R}\left(\frac{\mu_N}{\mu_B}\right),$$

where N_0 is Avogadro's number and $R = N_0 k_B$ is the gas constant per mole. $\xi = (H/v)\times 47.06 = 3.185$ cm^2 K in our case ($H = 25$ kG, $v = 3.694\times 10^5$ cm/sec).

We now state briefly some improvements made to the equipment described in Ref. 5.

To obtain a good stability of amplitude and phase of the rf fields, capacitive dividers pick up the rf field close to each coil. The amplitudes of the pickup control voltages are used to drive the respective automatic gain control states which hold the amplitude constant to better than 0.1%. At the same time, the phase difference between the two signals is measured and used to stabilize the relative phase between the two rf coils to better than 0.1 deg.

The dc magnetic field H_0 is stabilized through the NMR of a proton sample placed outside the cryostat. A long-term stability of the order of 50 mG is achieved, corresponding to a phase shift of the order of 1 deg.

The dynamic polarizations have been obtained in a conventional He^4 cryostat using a 70-GHz microwave source (the static field is about 25 kG). For static polarizations, a dilution refrigerator was used. It has been specially designed for simple operation, easy positioning and interchange of samples, well-defined temperature of the samples, and a minimum amount of He^3 in the path of the neutron beam. A detailed description of this cryostat will be given elsewhere.[6] The lowest temperature reached inside the dilution chamber was of the order of 20 mK. However, for most samples, a higher limit was set by the very long cool-down times. This is due to the conjunction of the Kapitza boundary resistance and nuclear heat capacity which leads to a very steep temperature dependence of the cooling times. The temperature was measured by a carbon resistor calibrated as follows: The value of $(2.10\pm 0.02)\mu_B$ for $\mu^*(V^{51})$ was obtained between 1 and 4.2 K using the He^4 vapor pressure as a temperature scale (a value in excellent agreement with the known spin-incoherent scattering cross-section value[7]). Then a measurement of the precession in V^{51} down to 40 mK provided, through formula (1), a value of the temperature against which the resistor was calibrated.

As an example, a plot of α against $1/T$ for Al^{27} is given in Fig. 1. At temperatures below 50 mK, where the arrows indicate the time sequence of the measurements, there is clear evidence that the sample does not follow the temperature changes in the dilution chamber.

Results obtained for seven nuclei are given in Table I. Two values of μ^* have also been obtained by dynamic polarization: for Li^7 in a LiF single crystal, and for Al^{27} in a ruby single crystal. All other results have been obtained with static polarizations in the dilution refrigerator. The room-temperature densities used to calcu-

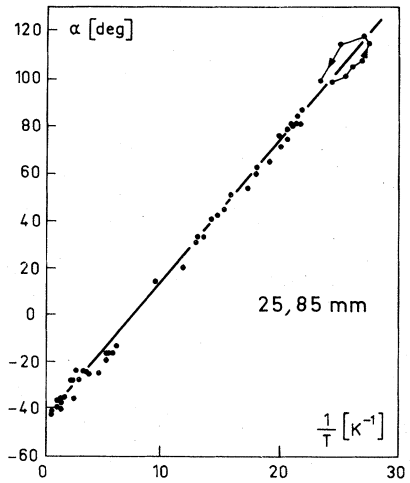

FIG. 1. Observed variation of the extra precession angle α with $1/T$ for Al^{27}.

TABLE I. Experimental values of μ^* and of $a_+ - a_-$ for seven nuclei. For comparison, values for $a_+ - a_-$ obtained from cross-section measurements are also given.

Isotope	Spin	d (g cm^{-3})	$\alpha T/l$ (deg cm^{-1} K)	μ^*/μ_B	$a_+ - a_-$ (10^{-12} cm)	$\lvert a_+ - a_- \rvert_\sigma$ (10^{-12} cm)	T_{min}[b] (K)
Li^7	3/2	0.540	15.8	-0.62 ± 0.03	-0.45 ± 0.02	0.52	0.100
				-0.65 ± 0.03[a]	-0.47 ± 0.02		
Al^{27}	5/2	2.70	2.39	$+0.077 \pm 0.004$	$+0.050 \pm 0.003$	•••	0.037
				$+0.088 \pm 0.010$[a]	$+0.057 \pm 0.006$		
Sc^{45}	7/2	2.99	48.2	$+1.95 \pm 0.04$	$+1.20 \pm 0.03$	1.45	0.083
Zr^{91}	5/2	6.51	0.66	$+0.74 \pm 0.10$	$+0.48 \pm 0.07$	•••	0.024
Nb^{93}	9/2	8.57	2.0	-0.046 ± 0.004	-0.028 ± 0.002	0.44	0.083
La^{139}	7/2	6.14	11.4	$+1.19 \pm 0.04$	$+0.73 \pm 0.03$	0.44	0.067
Ta^{181}	7/2	16.6	1.6	-0.096 ± 0.010	-0.059 ± 0.006	•••	0.071

[a] Measurements with dynamical nuclear polarization.
[b] Lowest temperature obtained in the experiment.

late μ^* from the slope $\alpha T/l$ and values of $a_+ - a_-$ derived from μ^* are included in Table I. For comparison, $|a_+ - a_-|$ obtained from the cross-section data, whenever possible, are also shown. No correction has been made for the change of density with temperature or for the contribution of the nuclear magnetization proper to the precession angle, since both corrections are in all cases below the error limits of our measurements.

It now appears that all neutron spin-dependent nuclear scattering lengths, with the possible exception of nuclei with very large absorption cross sections, are accessible to this method and that the main obstacles would be lack of time, lack of money (for the rare isotopes), and/or lack of motivation. Some possible applications of nuclear pseudomagnetism to the study of bulk matter have been discussed elsewhere.[3]

The authors (who are not nuclear physicists) would be grateful for suggestions of nuclei of particular interest. Is O^{17} of sufficient special interest to be investigated in spite of its very small isotopic abundance? Is an *accurate* measurement of μ^* for the deuteron of interest to specialists of the three-body problem? What about magic nuclei plus or minus a nucleon? For many isotopes differing by two neutrons, spins are identical and magnetic moments very near. Is the ratio of their pseudomagnetic moments worth investigating, etc.? We welcome suggestions.

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