Resonance depolarization of ^{12}B implanted in metallic and semiconductor hosts*

R. E. McDonald and T. K. McNab
Nuclear Sciences Laboratory, Lockheed Palo Alto Research Laboratory, Palo Alto, California 94304
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Resonance depolarization measurements have been made on ^{12}B implanted in the semiconducting hosts silicon, germanium, and silicon carbide, and in the face-centered cubic metal hosts platinum, rhodium, palladium, gold, copper, aluminum, and silver. The Knight shifts of ^{12}B in the metallic hosts have been obtained by comparison of the resonant frequencies in silicon and metallic hosts. The measured Knight shifts $\Delta\mu/\mu$ are: [Pt; $-10(3)\times10^{-5}$], [Rh; $4(4)\times10^{-5}$], [Pd; $11(4)\times10^{-5}$], [Au; $54(3)\times10^{-6}$], [Cu; $60(6)\times10^{-5}$], [Al; $66(9)\times10^{-5}$], and [Ag; $67(3)\times10^{-5}$]. The effective ^{12}B magnetic moment is determined to be $1.002\,82(2)\mu_N$ in Si, $1.002\,91(2)\mu_N$ in Ge, and $1.002\,87(2)\mu_N$ in SiC hosts.

[NUCLEAR MOMENTS $\mu(^{12}B)$ measured; resonance depolarization in Pt, Pd, Rh, Au, Ag, Cu, Al, Si, SiC, Ge hosts. Knight shifts measured.]

Resonance depolarization of ^{12}B implanted in several metallic hosts has been previously reported[1,2] and the Knight shifts in the metals Pt, Pd, and Au have been deduced using the measured relaxation times T_1 in these metals and the Korringa relation.[1] We have extended the range of metallic hosts used in the resonance depolarization studies of ^{12}B, and report here the first such studies with semiconductor hosts in which the Knight shift is absent because of the relatively low density of conduction electrons. The semiconductor measurements thus provide a zero point from which to measure the Knight shift in the metallic hosts.

^{12}B from the reaction $^{11}B(d,p)^{12}B$ at a deuteron energy of 1.5 MeV and a ^{12}B recoil angle of $45°\pm5°$ was implanted in the host under investigation in a uniform magnetic field of 5000 G. The field was produced by a 30.5 cm Varian magnet and stabilized with the aid of a proton resonance fluxmeter inserted near the center of the 7.6 cm magnet gap. The uncertainty associated with measuring the ratio of the magnetic field in the host of interest to that in the proton resonance fluxmeter is less than ±10 ppm.

The effective magnetic moment of ^{12}B in each host was determined by measuring the ratio of the depolarizing field frequency (DFF) to the proton resonance frequency. The DFF was stabilized using a computer-controlled servoloop in which the ratio of the two frequencies was measured for a 1 sec interval before the DFF was swept through its range (once every 36 sec) and compared with the value fed into the computer at the beginning of the run. Any change in the measured value resulted in an error signal being applied to the voltage-controlled Hewlett-Packard 8601A sweep generator supplying the DFF. The ratio of the two frequencies could be held constant to within ±5 ppm; however, FM jitter in the sweep generator gave rise to a broadening of the depolarization signal which was about 15 times larger than this value. Clearly all magnetic moment values are determined relative to the proton magnetic moment which is taken to be $2.792\,76\mu_N$.

The ^{12}B polarization was observed by measuring the fore-aft asymmetry of the β-ray flux in the magnetic field direction with two solid-state counter telescopes. The ratio of the counts from each

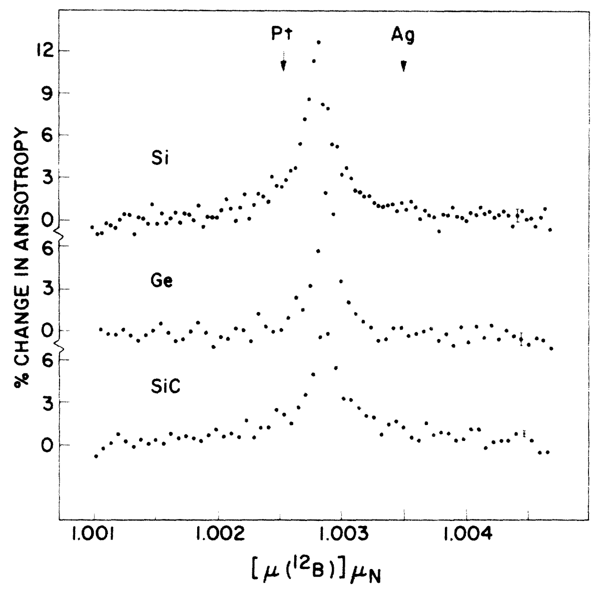

FIG. 1. Resonance depolarization spectra of ^{12}B implanted in the semiconducting hosts Si, Ge, and SiC. The ^{12}B was implanted while in a uniform field of 5000 G and the ^{12}B moment is measured relative to the proton magnetic moment which is taken to be $2.792\,76\mu_N$. The peak positions corresponding to Pt and Ag hosts are shown by the arrows.

TABLE I. Effective ^{12}B magnetic moment in various hosts.

Host	^{12}B polarization	This exp. [a]	$[\mu(^{12}B)]\mu_N$ (Ref. 1)	(Ref. 2)	$\Delta\mu/\mu$ ($\times 10^5$) This exp.	(Ref. 1)
Pt	15.4	1.002 72(2)	1.002 61(6)	1.002 70(11)	−10(3)	−24(15)
Rh	9.5	1.002 86(3)			4(4)	
Pd	15.4	1.002 93(4)	1.002 53(5)		11(4)	−32(15)
Au	12.8	1.003 36(2)	1.003 36(8)	1.003 37(12)	54(3)	51(15)
Cu	11.1	1.003 42(6)	1.003 24(6)	1.003 37(15)	60(6)	
Al	12.0	1.003 48(9)			66(9)	
Ag	14.0	1.003 49(2)			67(3)	
Si	9.4	1.002 82(2)				
Ge	7.2	1.002 91(2)				
SiC	6.5	1.002 87(2)				

[a] Relative to the proton magnetic moment, which is taken as $2.792\,76\mu_N$.

telescope was multiscaled in an on-line computer. Sufficient counts were accumulated to allow the determination of the peak position to within ±0.25 channels or ±13 ppm for the semiconductor, Ag, Pt, and Au hosts. However, peak positions of Al and Cu could be determined only to within ±90 and ±60 ppm, respectively, because of their large linewidth. The largest contribution then to determining the error in the effective magnetic moment of ^{12}B in each host is in the peak position measurement. The various errors given above lead, for instance, to an uncertainty in the semiconductor moment values of approximately ±20 ppm. In fact, measurements of the effective moment of ^{12}B were found to be reproducible to within ±20 ppm.

The Si and Ge hosts were thin single-crystal wafers with resistivities of 100–200 and of 1–10 Ω cm, respectively, and were etched with a solution of HF, HNO_3, and acetic acid. The SiC of purity 99.9%+ was in the form of several single crystal platelets oriented at random to each other. The metallic samples were cut from high purity (99.9%+) rolled foils.

Figure 1 shows the resonance depolarization spectra of ^{12}B implanted in Si, SiC, and Ge. The spread in magnetic moment results using the three semiconductor hosts gives some indication of the magnitude of the chemical shift experienced in semiconducting host materials. Table I lists the magnetic moment of ^{12}B in various hosts, uncorrected for Knight shift or chemical shift, together with the results of other investigators. It is seen from the table that our values of the effective magnetic moment agree with earlier measurements of Sugimoto *et al.* and (with the exception of the Pd result) of Williams *et al.* We have rechecked our Pd result in a separate experiment and find agreement with our earlier value for the Pd moment. The result quoted in the table is an average of the two measurements. We have no explanation for the discrepancy between our results and that of Williams *et al.*

Table I lists the value of the Knight shift of ^{12}B in each of the face-centered cubic metallic hosts expressed as an apparent shift in magnetic moment relative to the silicon host. The results for the Knight shift in Pt and Au thus obtained agree with the earlier results of Williams *et al.*, who calculated the Knight shift from relative shifts in Pt, Pd, and Au hosts using the measured relaxation rates and the Korringa relation, and obtain a value of $1.002\,85^{+15}_{-14}\mu_N$ for the ^{12}B magnetic moment. The present measurements avoid uncertainties in the application of the Korringa relationship and in measurements of T_1.

The greatest source of error in these Knight shift measurements derives from the unknown chemical shift of ^{12}B in the various hosts. Typically, chemical shifts are about 10% of the Knight shifts. In the present measurements the chemical shift is responsible for the spread of 90 parts in 10^6 in semiconductor host measurements. The measured effective ^{12}B magnetic moment in semiconductor hosts all agree within the limits of error with the earlier $\mu(^{12}B)$ deduced by Williams *et al.*

The apparent polarization of the ^{12}B in the hosts studied is also listed in Table I. These values were obtained from the change in β-ray anisotropy following reversal of the ^{12}B spin directions by adiabatic fast passage. This is a lower limit to the initial ^{12}B polarization, of course, since depolarization effects were not assessed in this experiment.

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