Magnetic dipole moment of ^{127}Sb and ^{129}Sb by nuclear magnetic resonance on oriented nuclei

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A series of low temperature nuclear orientation (LTNO) experiments has been initiated to measure accurately ground-state magnetic dipole moments of a sequence of odd-proton antimony isotopes up to the neutron shell closure at $N=82$ using the sensitive technique of nuclear magnetic resonance on oriented nuclei (NMR/ON). The main aim of this investigation is to clarify the single-particle+collective core coupling mechanism in the heavy antimony isotopes and its influence on the value of magnetic dipole moment. This paper reports results of precision measurement of the magnetic dipole moments of ^{127}Sb and ^{129}Sb.

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I. INTRODUCTION

Model calculations of heavy odd-*A* Sb isotopes have shown [1–3] that the ground state and low lying excitations of these nuclei can be well described assuming that the odd proton interacts with collective quadrupole and octupole vibrations of the underlying core. The main model ambiguity at present is in the description of collectivity of the core. Two approaches are considered: (i) a purely collective model including all core nucleons where the collective gyromagnetic ratio $g_R = Z/A$ and (ii) a core with reduced collectivity where only surface protons and nucleons contribute to the core magnetic dipole moment and the value of g_R is reduced with respect to Z/A [4]. To understand better the model separation of the single particle and the collective components contributing to the total magnetic dipole moment, the knowledge of experimental magnetic dipole moments of the 7/2+ ground state for the odd-even heavy antimony isotopes sequence from ^{127}Sb up to the $N=82$ neutron shell closure at ^{133}Sb is needed. Preliminary calculations showed that to achieve sufficient sensitivity for meaningful comparison of experimental data with model predictions accurate technique of nuclear magnetic resonance on oriented nuclei (NMR/ON) must be used, allowing measurements with a precision of better than 1 part in 1000 [5]. Experimental results obtained for ^{127}Sb and ^{129}Sb are presented in this paper. Magnetic dipole moments of ground states of ^{131}Sb and ^{133}Sb and a full theoretical analysis of the results will be the subject of a forthcoming publication.

II. EXPERIMENTAL METHOD

The polarization of an ensemble of nuclei for the method of NMR/ON is achieved with low temperatures and strong magnetic fields. The angular distribution of parity conserving radiation from such an ensemble is given by

$$W(\theta)=1+f\sum_{\lambda=1}^{L} B_\lambda U_\lambda A_\lambda Q_\lambda P_\lambda(\cos\theta), \qquad (1)$$

where all symbols have their conventional meaning in the context of low temperature nuclear orientation (LTNO) [6]. The necessary condition for appreciable polarization in LTNO is that the thermal energy, k_{BT}, is smaller than the energy between nuclear Zeeman-split substates.

The hyperfine field acting at Sb nuclei in ferromagnetic iron is sufficiently strong to achieve appreciable polarization at temperature of 20 mK and below. The iron sample is magnetized to saturation by an applied field of order 1 T which defines the axis of orientation.

Once the ensemble of nuclei is polarized a modulated rf field is applied perpendicularly to the applied field at a frequency matching the energy separation between the magnetic substates. The polarization is destroyed and the radiation emission anisotropy lost. Inhomogeneous broadening of the resonance in ferromagnetic metals results in the need to modulate the rf field over a frequency range comparable to the linewidth to achieve observable resonant destruction of anisotropy. To maintain other effects of the rf field (e.g., eddy current heating) constant and identify the true nuclear resonance, the rf power is kept on continuously and only the modulation is turned on and off. A quantitative measure of the effect is the so-called destruction of anisotropy

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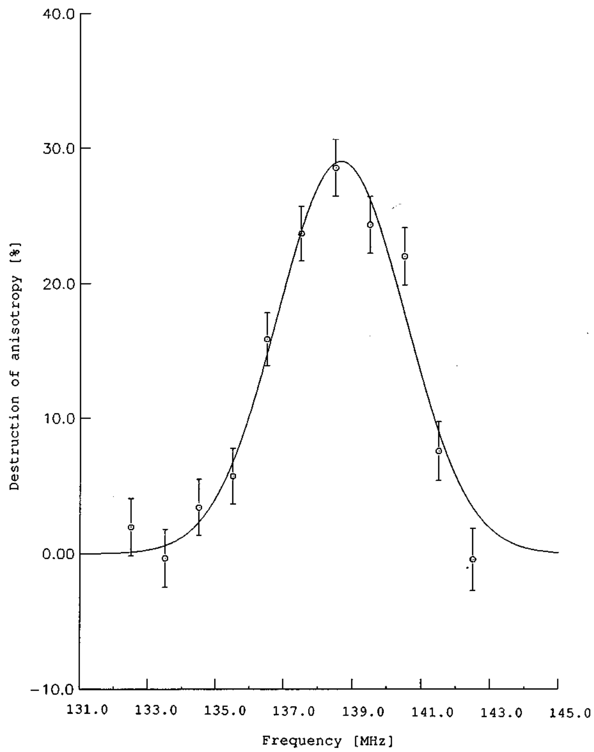

FIG. 1. NMR/ON on ^{127}Sb was performed using two samples. The results were found consistent and the weighted average of all experiments yields a magnetic moment of $\mu = 2.697(6)\ \mu_N$. Data for D against rf for $B_{\text{applied}} = 0.25$ T is shown in the figure. The peak is located at $f = 138.7(1)$ MHz.

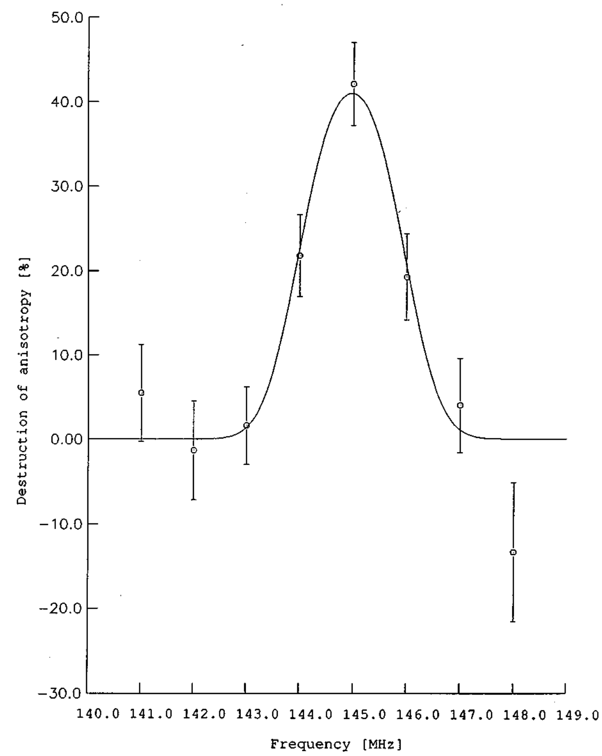

FIG. 2. The short half-life, $T_{1/2} = 4.1$ h, of the ^{129}Sb activity only permitted two sweeps to be performed. Data for D against rf for $B_{\text{applied}} = 0.3$ T can be seen in the figure. The peak is located at $f = 144.97(9)$ MHz yielding $\mu = 2.817(10)\ \mu_N$.

$$D = \frac{N_{\text{on}} - N_{\text{off}}}{N_{\text{warm}} - N_{\text{off}}}, \tag{2}$$

where N_{on} is the number of counts per time unit when the modulation is on, N_{off} the number of counts when modulation is off, and N_{warm} the number of counts at a high temperature (1 K) where the polarization is insignificant. A detailed description of the technique can be found in [5].

The resonance center frequency, ν_0, can be expressed as

$$\nu_0 = \frac{|\mu|}{Ih}[B_{\text{hf}} + B_{\text{applied}}(1+K)], \tag{3}$$

where μ is the magnetic moment of the state, I the spin, and K the Knight shift taking account of conduction electron paramagnetism and the associated hyperfine interaction. Using the Korringa constant C_k for ^{125}Sb in iron [7] and the Korringa relationship [8] between C_k and the Knight shift the latter has been estimated to be $\approx 2 \times 10^{-3}$ for antimony in iron. This is sufficiently small to adopt $K = 0$ in this work.

The most accurate determination of the hyperfine field for antimony in an iron host is the spin-echo experiment of Koi *et al.* [9]. They give $B_{\text{hf}} = +23.387(10)$ which has been used throughout this work.

The sources were prepared at the Department of Neutron Research of Uppsala University at Studsvik in Sweden. The activity was produced by thermal fission in neutron irradiated ^{235}U and separated with the on-line magnetic mass separator OSIRIS. It was implanted on-line at 40 keV into a rolled and polished 99.99% pure iron foil.

The samples were brought to Oxford and loaded into a ^{3}He-^{4}He dilution refrigerator at liquid helium temperature.

III. RESULTS

NMR/ON on ^{127}Sb [10] was performed using two different samples, at each experiment several frequency sweeps were performed differing in direction, rf amplitude, applied

TABLE I. A summary of the two experiments performed with a ^{127}Sb sample.

Sample	Search range (MHz)	Frequency step (MHz)	Modulation (MHz)	B_{applied} (T)	ν_0 (MHz)
1	136.0–142.5	0.5	0.5	0.30(1)	139.6(2)
2	132.5–142.5	1.0	1.0	0.25(1)	138.7(1)

TABLE II. A summary of the two experiments performed with a ^{129}Sb sample.

Sample	Search range (MHz)	Frequency step (MHz)	Modulation (MHz)	B_{applied} (T)	ν_0 (MHz)
1	133.0–148.0	1.0	1.0	0.30(1)	↓
1	143.0–147.0	1.0	1.0	0.30(1)	144.97(9)

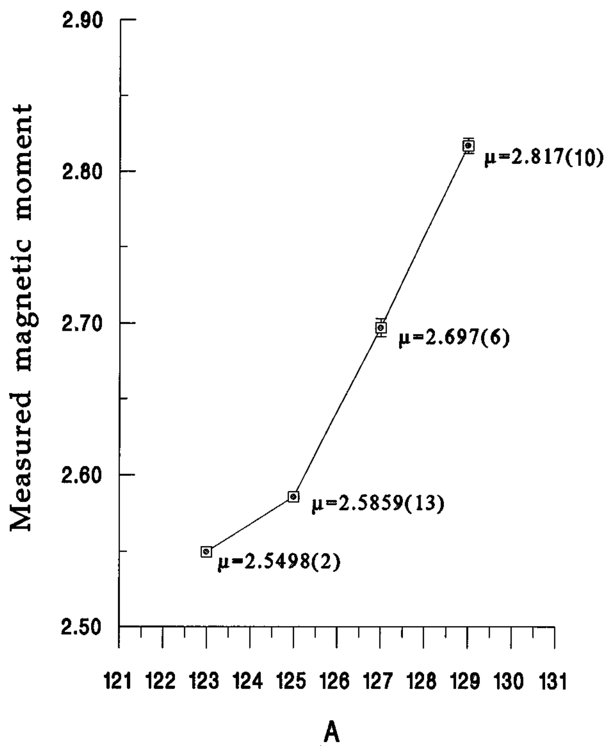

FIG. 3. The measured magnetic moments, in units of nuclear magnetons [μ_N], for the odd-proton heavy antimony isotopes from $A=123$ to 129 shows a steady increase. This hints at a possible very small collective g factor in this region. The measured values for ^{123}Sb and ^{125}Sb are taken from Refs. [12] and [13], respectively. However, the moment for ^{125}Sb has been recalculated using the correct hyperfine field from [9].

field, and frequency step size. The results were found consistent and the weighted average of all the experiments yields a magnetic moment of $\mu=2.697(6)$ μ_N allowing for a 3% error in the applied field. Data for D against rf for $B_{\text{applied}}=0.25$ T are shown in Fig. 1 and a summary of the experiments is given in Table I.

The short half-life, $T_{1/2}=4.1$ h, of the ^{129}Sb activity only permitted two sweeps to be performed; a first exploratory sweep in search of the resonance and a second more detailed over the resonance (see Fig. 2). The center frequency was found at $\nu_0=144.97(9)$ MHz yielding $\mu=2.817(10)$ μ_N for $B_{\text{applied}}=0.30(1)$ T. Data for D against rf for $B_{\text{applied}}=0.3$ T can be seen in Fig. 2 and a summary of the experiment can be found in Table II. The errors quoted are the errors of the fit.

IV. DISCUSSION

We have reported here on results from NMR/ON experiments on ^{127}Sb and ^{129}Sb. The purpose of our experiments is, as outlined in the Introduction, to measure the unknown magnetic moments of the odd proton heavy antimony isotopes up to the neutron shell closure at $N=82$ and through particle core coupling calculations shed light on the influence of contribution of the even-even core to the magnetic moment. The size of this contribution is determined by the collective g factor which in itself is a measure of the collectivity of the nucleus. However, the correction to the magnetic moment due to collective admixtures is only of second order (see, e.g. [11]) and for a reliable interpretation it is crucial to obtain data for the whole sequence of $I^{\pi}=7/2^{+}$ magnetic dipole moments up to the neutron shell closure, where a relatively dramatic change is expected in the collective admixture. Nevertheless, already at this early stage, with ^{131}Sb and ^{133}Sb moments missing for the complete sequence up to the neutron shell closure, we can observe a very interesting trend; a steady increase of the moments with increasing N (see Fig. 3). This hints at [14] a very small collective g factor in this region, suggesting that only a few outer nucleons are responsible for collectivity of the core.

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