Submitted to Phys. Rev. C. UM-P-81/24.

Velocity Dependence of Transient Hyperfine Field at Pt Ions Rapidly Recoiling Through Magnetized Fe

A.E. Stuchbery, C.G. Ryan, and H.H. Bolotin

School of Physics, University of Melbourne, Parkville, Victoria 3052, Australia

UNIVERSITY OF MELBOURNE

SCHOOL OF PHYSICS

PARKVILLE VICTORIA AUSTRALIA

UM-P-81/24

Submitted to Phys. Rev. C

Velocity Dependence of Transient Hyperfine Field at Pt Ions Rapidly Recoiling Through Magnetized Fe

A.E. Stuchbery, C.G. Ryan, and H.H. Bolotin

School of Physics, University of Melbourne, Parkville, Victoria 3052, Australia

ABSTRACT: The velocity-dependence of the transient hyperfine magnetic field acting at nuclei of ^{196}Pt ions rapidly recoiling through thin magnetized Fe was investigated at a number of recoil velocities. The state of interest (2_1^+) was populated by Coulomb excitation using beams of 80- and 120-MeV ^{32}S and 150- and 220-MeV ^{58}Ni ions. The $2_1^+ \rightarrow 0_1^+$ γ-ray angular distribution precession measurements were carried out in coincidence with backscattered projectiles. From these results, the strength of the transient field acting on Pt ions recoiling through magnetized Fe with average velocities in the extended range $2.14 \leq \langle v/v_0 \rangle \leq 4.82$ ($v_0 = c/137$) was found to be consistent with a linear velocity dependence and to be incompatible with the specific $v^{0.45\pm0.18}$ dependence which has been previously reported to account well for all ions in the mass range from oxygen through samarium. This seemingly singular behaviour for Pt and other ions in the Pt mass vicinity is discussed.

NUCLEAR REACTIONS $^{196}Pt(^{32}S,^{32}S')^{196}Pt(2_1^+)$, $^{196}Pt(^{58}Ni,^{58}Ni')^{196}Pt(2_1^+)$, E_S = 80 and 120 MeV, E_{Ni} = 150 and 220 MeV, enriched target; measured $W(\theta,H,\infty)$ in thin polarized Fe. Deduced transient field and velocity dependence of Pt$\underline{Fe}$ for $v/c \leq 3.84\%$.

I. Introduction

Following the discovery[1] of large transient hyperfine magnetic fields acting at the nuclei of ions swiftly traversing polarized ferromagnetic materials, a considerable number of investigations[2-4] have been reported which have been addressed to the elucidation of the dependence of the strength of this magnetic field on ion parameters, as well as to an understanding of the ion-solid interaction mechanism responsible for it.

From analysis of the body of transient field data reported at the time for ions ranging from oxygen to samarium, the Rutgers group[2] found that the dependence of the field strength on ion velocity, v, and atomic number, Z, could be fit well by a "universal" parameterization of the form

$$B(v,Z) = \underline{a}\ (v/v_o)^p\ Z^q\ \mu_B N_p \qquad (1)$$

where μ_B and N_p are, respectively, the Bohr magneton and the density of polarized electrons in the saturated ferromagnetic foil through which the ion travelled. Their best fit to the existing data was found for $\underline{a}$ = 96.7 ± 1.6, p = 0.45 ± 0.18, and q = 1.1 ± 0.2 for ion velocities in the range $1.5 \leq v/v_o \leq 5$ (v_o = c/137). A subsequent investigation[5] of the field strength manifest at somewhat higher speeds (up to v/v_o = 7) for Pd ions was also in accord with this near-square-root velocity dependence (i.e. p = 0.41 ± 0.15).

However, the Rutgers group noted[2,3] that the available data for Pt ions did not appear to follow this prescription; these data constituted "glaring exceptions" to the velocity dependence displayed by virtually all lower-Z transient field strength measurements for $1.5 \leq v/v_0 \leq 7$. Yet, the single transient field measurement[4] for Os ions (Z = 76) at $\langle v/v_0 \rangle = 2$ appears to be in accord with the field strength parameterization[2] for the lower-Z ions.

It is clear from the foregoing that the field behaviour in the Pt mass region is still an open empirical question.

The basic mechanism responsible for the occurrence of the transient field is not quantitatively understood at present. The studies of Dybdal et al.[6,7] showed a strong correlation between the strength of the observed transient field and the electron K-vacancy fraction produced as a function of v/v_0 in O, F, and Si ions slowing down in ferromagnetic media, indicating that the main contribution to the field originates from the polarization of bound projectile electrons; however, it is still unclear how the polarization of the ferromagnetic electrons is transferred to the bound unpaired electron of the ion[7]. Further, none of the forms of parameterization of the transient field yet proposed are based upon any specific presumed underlying ion-solid interaction which may give rise to it. Thus, the non-universality of the fits of these parameterizations to the overall extant body of data, while at this stage neither clouding nor clarifying our understanding of the effect, does leave the v- and Z-dependence of the transient field ambiguous.

As the Pt field strength measurements[2,3] available at the time of the Rutgers parameterization[2] were by-products of investigations with disparate experimental objectives and spanned only the limited average velocity range $2.1 \le \langle v/v_0 \rangle \le 2.9$, it was apparent that more systematic studies of the transient field for Pt ions over a broader velocity range were desirable. One such investigation[8] of the strength of the transient field manifest at the nuclei of Pt ions traversing thin, magnetized Fe foils with relatively low velocities in the range $1.25 \le \langle v/v_0 \rangle \le 2.65$ found no systematic deviation from a linear velocity dependence for it.

The present experimental investigation was undertaken to systematically extend measurements of the velocity dependence of the transient field for Pt ions recoiling through polarized iron to higher average velocities. The velocity domain of the present investigation $[2.14 \le \langle v/v_0 \rangle \le 4.82]$ was selected to augment and extend the previously reported systematic studies[8] carried out over the somewhat lower and partially overlapping velocity range.

II. Experimental procedures

The nuclear state of interest (i.e. 2_1^+ ^{196}Pt) was populated by Coulomb excitation using beams of 80-MeV $^{32}S^{7+}$, 120-MeV $^{32}S^{8+}$, 150-MeV $^{56}Ni^{10+}$, and 220-MeV $^{56}Ni^{18+}$ from the Australian National

University 14UD Pelletron tandem accelerator. The target was prepared by electrodeposition of ^{196}Pt (enriched to 97.5%) onto a ~1 μm Fe foil (previously annealed in an H_2 atmosphere). This foil was backed with a thick (~ 20 μm) evaporated Cu layer that provided a magnetically perturbation-free environment in which the recoiling Pt ions stopped; the Cu layer also served as the beam dump. The target and Fe foil thicknesses were determined to be 1.27 ± 0.06 mg cm^{-2} and 1.13 ± 0.04 μm, respectively, by Rutherford scattering of 3-MeV protons from the University of Melbourne 5U Pelletron accelerator.

Although magnetometer tests showed that 100 Oe was adequate for the purpose, we employed a magnetizing field of 300 Oe to ensure complete saturation of the thin Fe foil. The triple-layered target was placed between the pole tips of a diminutive electromagnet which provided this field at the Fe foil;the field direction, normal to the beam, was automatically reversed at frequent intervals.

The triple-layered, thin Fe foil experimental technique used to measure the precession of the $2_1^+ \rightarrow 0_1^+$ γ-ray angular distribution has been described in detail elsewhere[3,9]. Two 60-cm^3 Ge(Li) detectors placed 5 cm from the target at ±70° to the beam direction recorded the 355-keV $2_1^+ \rightarrow 0_1^+$ transition γ-ray in coincidence with beam projectile ions backscattered from the target in the angular range 147-166° detected in an annular surface-barrier detector. The coincidence requirement resulted in events recorded for ^{196}Pt ions which recoiled in forward cones of half angles ~ 8° and ~ 7° for the ^{32}S and ^{58}Ni beams, respectively. The trajectories of both the incident and back-scattered projectile ions were shielded from the field of the electromagnet to reduce beam-bending effects to negligible proportion; beam-bending was <0.09 mrad for all beams and beam energies used in the present work, as calculated from measurements of the fringing field as a function of distance from the Fe foil up-stream of the target with the soft iron shielding core in place.

Reversal of the polarizing field at frequent intervals served to minimize systematic errors and to provide appropriate normalization of the recorded field-up(↑) and field-down(↓) data, as the field direction was flipped after a preset number of backscattered ions from the target was registered in the singles spectrum of the annular detector.

To ensure internal consistency of precession measurements at all recoil velocities studied, the same triple-layered target was employed with the various beam ions and beam energies used. The thin (~1 μm) Fe foil was employed so that the recoiling Pt ions suffered only a relatively small change in velocity during traversal of the foil. As the excited Pt ions recoiled through the Fe to stop in the perturbation-free Cu backing, they were not subject to the static field in the ferromagnetic foil.

The unperturbed angular distribution of the $2_1^+ \rightarrow 0_1^+$ transition in ^{196}Pt was measured in each case for the identical geometrical arrangement used in the precession studies. Any local γ-ray absorption non-uniformities due to thickness variations in the target chamber walls, etc. were determined and corrected for by measurement, as a function of angle, of the detected rates of γ-rays from a ^{152}Eu source placed at the beam spot location.

For a given γ-ray angular distribution, $W(\theta)$, it can readily be shown that the counting rate, N, recorded by a gamma-ray detector at a specified distance from the target is most sensitive to the transient field-induced angular precession, $\Delta\theta$, of that distribution when located at that angle θ_γ to the beam such that S^2N is a maximum [S is the logarithmic derivative of $W(\theta)$]. For the target-to-detector distance of the Ge(Li) detectors employed in the present investigations, θ_γ was approximately $\pm 70^\circ$ for the $2_1^+ \rightarrow 0_1^+$ transition for all beam energies and projectile ions employed. Consequently, the two detectors were positioned at these angles to the beam direction.

Coincidences between each γ-ray detector and the annular particle detector were recorded in an event-by-event, multiparameter mode on magnetic tape (γ-ray, particle, and time-analogue converted pulse-heights, plus a field-up/field-down tag bit). The coincidence spectrum associated with each field direction was obtained separately in off-line tape play-back sorts. Gates set on the detected projectiles backscattered from the Pt target eliminated all Fe and Cu γ-rays from the sorted spectra. Chance coincidence rates, although small throughout the experiment, were duly subtracted in the analysis.

Analysis of the data followed the prescription of Stuchbery et al.[5,10] employing the previously determined gyromagnetic ratios[11] and branching ratios[12] of all populated states higher than the 2_1^+ level which feed it. As the mean life of the 2_1^+ in ^{196}Pt [46.5 ± 2.1 psec[12]] is long compared to the transit time of the Pt ions through the ~1 μm Fe foil, corrections for decay in flight while in Fe were negligible [the longest transit time (0.24 psec) in the present studies pertained for the 80-MeV ^{32}S beam measurement; the transit times were calculated from the known kinematics and the measured target and Fe foil thicknesses on the basis of the stopping powers of Zeigler[13]].

III. Results

Table I summarizes the experimental particulars and results of the present investigation, as well as of similar prior recent precession measurements[10,11] of the $2_1^+ \rightarrow 0_1^+$ ^{196}Pt transition that employed a thicker (6.4 μm) Fe foil. The time-averaged transient fields, $\langle B \rangle = \frac{1}{T_{Fe}} (\frac{\Delta\theta}{g})(\frac{\hbar}{\mu_N})$, experienced by the nuclei of the ^{196}Pt ions over their transit times, T_{Fe}, through the Fe foils and the average velocities, $\langle v/v_0 \rangle$, of the ions traversing the foil thickness L [i.e. $\langle v/v_0 \rangle = (\frac{L}{T_{Fe}})(\frac{1}{v_0})$] are also presented.

The next-to-last column in Table I presents the values of a_{LIN} calculated from these data on the presumption of a linear velocity dependence for the transient field strength, i.e.

$$\frac{\Delta\theta}{g} = -\frac{\mu_N}{\hbar}\int_0^T B dt = -a_{LIN} Z \frac{\mu_N}{\hbar} (\mu_B N_p)\int_0^L \frac{v}{v_0}\frac{dx}{v}$$

whence

$$\frac{\Delta\theta}{g} = -a_{LIN} Z \frac{\mu_N}{\hbar} (\mu_B N_p) L, \qquad (2)$$

where L is the thicknesses of the ferromagnetic foil traversed by the ions and μ_N is the nuclear magneton (for a fully saturated Fe foil $\mu_B N_p$ = 1752 gauss).

The measured values of $\Delta\theta$ are compared in Table II with those predicted on the basis of the Rutgers parameterization[2)] (eq. 1) and with the values of $\Delta\theta$ predicted on the basis of a linearly velocity-dependent transient field (eq. 2). For the former set of predictions, the stopping powers of Zeigler[13)] were employed; while for the latter set, the value of a_{LIN} = 58.2 ± 1.7, the weighted average of the experimental values (next to last column of Table I), was adopted. The experimental $\Delta\theta$ values when compared with the values predicted by the Rutgers parameterization (i.e. $B = v^p Z^q$, with p = 0.45 and q = 1.1) yielded a χ^2_ν -value per degree of freedom of 44.6; while comparison with the predictions based on a linearly velocity-dependent field (i.e. $B = vZ$) gave $\chi^2_\nu = 1.1$.

On the basis of the ^{196}Pt data presented in Table I, the present experimental results, while clearly inconsistent with a near square-root velocity dependence, are in excellent agreement with a transient field strength which depends linearly on the velocity of the recoiling ion. This is in agreement with the conclusions of Grace et al.[8] who found that the strength of the transient field did not appear to display any systematic deviation from linearity over the lower span of average velocities $1.25 \leq \langle v/v_0 \rangle \leq 2.7$ with which Pt ions recoiled through a thin Fe foil.

Figure 1 displays the average transient field experienced at the nuclei of Pt ions recoiling through Fe foils with mean velocities $\langle v/v_0 \rangle$ derived from the present data and the experimental findings of the Oxford group[8]. As neither we nor they observe any systematic deviation from a linear velocity dependence, the two sets of data presented in this figure have been normalized by their separately defined average a_{LIN} values (eq. 2). The straight solid curve in the figure represents the weighted least-squares fit of these combined data to a presumed linear velocity dependence ($\chi^2_\nu = 0.8$). Also shown is the $\langle B \rangle$ vs. $\langle v/v_0 \rangle$ prediction based upon the parameterization (eq. 1) the Rutgers group[2] obtained from their fits to oxygen through samarium mass range precession data. It is clear that this latter parameterization is inconsistent with these experimental data.

Moreover, the velocity dependence ($v^{0.45}$) specified by the Rutgers parameterization[2] has been least-squares fitted to only the data of Table I and is shown in Fig. 1 by the dashed curved line ($\chi^2_\nu = 2.84$ for 5 degrees of freedom - a probability of only 0.015 that χ^2_ν this large or larger would be obtained by chance). Clearly a near square-root velocity dependence is strongly disfavoured by the present experimental results.

Finally, we note that the transient field measurements reported[14] for Tm ions (Z = 69) appear more in accord with the present velocity dependence found for Pt ions than with that observed for lower-Z (oxygen through samarium) ions.

IV. Conclusions

It has been empirically determined from the present systematic set of precession studies that the strength of the transient field manifest at the nuclei of Pt ions recoiling through magnetized Fe foils with mean velocities in the range $2.14 \leq \langle v/v_0 \rangle \leq 4.82$ is consistent with a linear velocity dependence and is out of keeping with the near square-root velocity dependence that appears to pertain for lower-Z ions in the mass range from oxygen to samarium. This finding is in agreement with that reported by prior workers[8] for Pt ions recoiling with smaller mean velocities in the range $1.25 \leq \langle v/v_0 \rangle \leq 2.7$. Taken in conjunction, the available evidence is compatible with a linear velocity dependence of the transient field acting on Pt ions over the broad span of mean recoil velocities from $1.25 \leq \langle v/v_0 \rangle \leq 4.82$.

The somewhat disconcerting disparity in the velocity dependencies apparently exhibited by the lower- and higher-Z ions recoiling through ferromagnetic hosts tends to point to the need for other systematic sets of transient field measurements which, when taken together with the presently available data, may serve to define a more universal dependence of the transient field on ion parameters.

This incompatibility between the forms of the velocity dependence observed for lower- and higher-Z ions ($v^{\sim 0.45}$ and $v^{\sim 1}$, respectively) suggests strongly that the separable-variable form with which the v- and Z-dependencies have been treated in virtually all prior parameterizations of the transient field is not justified.

The lack of a universal parameterization of the transient field strength necessitates that measurements of g-factors of excited states in which these large fields are exploited must incorporate a reliable form of field strength normalization.

V. Acknowledgements

The authors wish to express their sincere appreciation for the cooperation and support provided by Dr. T. Ophel and the staff of the Australian National University 14 UD Pelletron tandem accelerator and to Dr. T. Aoki and P.B. Foot for aid provided in facets of data acquisition. Two of us (A.E.S. and C.G.R.) acknowledge the benefit of Commonwealth Postgraduate Awards. This work was supported in part by grants from the Australian Research Grants Committee and Budget Rent-a-Car (Australia) for which we are most appreciative.

References

1. R.R. Borchers, B. Herskind, J.D. Bronson, L. Grodzins, R. Kalish and D.E. Murnick, Phys. Rev. Lett. 20 (1968) 424.

2. N.K.B. Shu, D. Melnick, J.M. Brennan, W. Semmler and N. Benczer-Koller, Phys. Rev. C21 (1980) 1828, and references cited therein.

3. N. Benczer-Koller, M. Hass, and J. Sak, in Annual Review of Nuclear and Particle Sciences, eds. J.D. Jackson, H.E. Gove and R.F. Schwitters, Vol. 30, 1980, and references cited therein.

4. N. Benczer-Koller, private communication.

5. A.E. Stuchbery, C.G. Ryan, H.H. Bolotin and S.H. Sie, Phys. Rev. C (in press).

6. K. Dybdal, J.L. Eberhardt and N. Rud, Phys. Rev. Lett. 42 (1979) 592.

7. K. Dybdal, J.S. Forster and N. Rud, Nucl. Instr. and Methods 170 (1980) 233.

8. M.A. Grace, J. de Raedt, J. Billowes, B.J. Murphy, and A. Pakou, Report on Nuclear Structure Research, Nuclear Physics Laboratory, University of Oxford, September 1980 (unpublished).

9. N. Benczer-Koller, M. Hass, J.M. Brennan, and H.T. King, in Proceedings of the International Conference on Nuclear Structure, Tokyo, 1977, published in J. Phys. Soc. Japan 44 (1978) Suppl. p. 341-344.

10. A.E. Stuchbery, C.G. Ryan, H.H. Bolotin, I. Morrison, and S.H. Sie, Nucl. Phys. A (in press).

11. A.E. Stuchbery, C.G. Ryan, I. Morrison, and H.H. Bolotin, Nucl. Phys. A (to be published).

12. H.H. Bolotin, A.E. Stuchbery, I. Morrison, D.L. Kennedy, C.G. Ryan, and S.H. Sie, Nucl. Phys. A (to be published).

13. J.F. Zeigler, Appl. Phys. Lett. 31 (1977) 544.

14. O. Häusser, D. Ward, H.R. Andrews, N. Rud, P. Skensved, and C. Broude, Nucl. Instr. Meth. 169 (1980) 539.

15. Table of Isotopes, seventh edition, edited by C.M. Lederer and V.S. Shirley (John Wiley and Sons, New York, 1978), appendix VII, in which previously reported measurements of the g-factors of the 2_1^+ state in ^{196}Pt are tabulated and referenced. The mean value of these measurements is $g(2_1^+) = 0.326 \pm 0.014$.

Table 1. Experimental particulars and results for ^{196}Pt ions traversing magnetized Fe foils[a].

Beam	E_i^b (MeV)	E_o^b (MeV)	$(v/v_o)_i^b$	$(v/v_o)_o^b$	$\langle v/v_o\rangle^c$	L(μm)[d]	T_{Pt}^e (psec)	T_{Fe}^e (psec)	$\epsilon(70^o)^f$ (×10³)	$S(70^o)^g$	Measured Δθ(mrad)	$\langle B\rangle(kT)^h$	a_{LIN}^i	Ref.
80-MeV ^{32}S	30.8	16.0	2.52	1.81	2.14	1.13	0.053	0.241	15.5±1.6	-2.30±0.09	-6.7±0.7	1.78±0.19	60.8±6.4	Present
120-MeV ^{32}S	48.2	29.4	3.15	2.46	2.77	1.13	0.042	0.186	14.7±2.0	-2.12±0.14	-7.0±1.0	2.41±0.34	63.6±9.1	Present
150-MeV ^{58}Ni	88.2	59.5	4.26	3.50	3.85	1.13	0.031	0.134	20.4±1.8	-2.68±0.08	-7.6±0.7	3.63±0.33	69.1±6.4	Present
220-MeV ^{58}Ni	134.3	97.9	5.25	4.49	4.82	1.13	0.025	0.107	12.0±1.3	-2.15±0.08	-5.6±0.6	3.35±0.36	50.8±5.4	Present
220-MeV ^{58}Ni	136.1	5.8	5.30	1.09	2.68	6.4[j]	0.022	1.09	94.6±1.7	-2.58±0.12	-35.5±1.4	2.09±0.08	57.0±2.2	11
220-MeV ^{58}Ni	133.4	5.2	5.24	1.04	2.61	6.4[j]	0.026	1.12	92.8±5.2	-2.68±0.11	-35.5±2.0	2.03±0.11	57.0±3.2	10

a Specifics for measured precession of $2_1^+ \to 0_1^+$ γ-ray angular distribution. Mean life of 2_1^+ state: 46.5 ± 2.1 psec (ref. 12).

b Energies, $E_i(E_o)$, and velocities, $(v/v_o)_i[(v/v_o)_o]$, of Pt ion entering (leaving) Fe foil; v_o = c/137.

c Mean recoil velocity of Pt ion in Fe foil.

d Measured thickness of Fe foil.

e Mean transit time of Pt ion through Pt target (T_{Pt}) and Fe foil (T_{Fe}).

f The experimental measured ratio $\epsilon = (1-\rho)/(1+\rho)$ multiplied by 10^3, where $\rho = \{[N\uparrow(+)N\downarrow(-)]/[N\downarrow(+)N\uparrow(-)]\}^{1/2}$ measured with detectors positioned at (±) the specified angle, and N↑(N↓) are the normalized counting rates recorded for polarizing field up(down).

g Measured values of S [the logarithmic derivative of W(θ)] for the $2_1^+ \to 0_1^+$ transition at the designated angle for the same experimental geometry as employed in the precession measurements (see text).

h The mean value of the transient field experienced at the nucleus of the ^{196}Pt ions while in the Fe foil; obtained using the measured g-factor of the 2_1^+ level [g = 0.326 ± 0.014 (ref. 15)], and the transit time (T_{Fe}) of the ion through the Fe foil.

i These values of a_{LIN} were obtained assuming $Z^{1.0}$.

j This thickness was reported (refs. 10 and 11) to be 5 μm from specifications of supplier (Goodfellow Metals), but has subsequently been measured in a complementary Rutherford scattering determination to be 6.4 ± 0.3 μm.

Table II. Comparison of the presently measured $\Delta\theta$ values with those predicted on the bases of a linear and near-square-root velocity dependence of the transient field acting on swift ^{196}Pt ions recoiling through magnetized Fe foils.

$\langle v/v_o \rangle$[a]	$L(\mu m)$[b]	Measured $\Delta\theta$ (mrad)	Predicted $\Delta\theta$ (mrad)[c] $[B \propto v]$[d]	$[B \propto v^{0.45}]$[e]
2.14	1.13	-6.7±0.7	-6.35	-10.91
2.61	6.4	-35.5±2.0	-35.96	-53.5
2.68	6.4	-35.5±1.4	-35.96	-53.1
2.77	1.13	-7.0±1.0	-6.35	-9.78
3.85	1.13	-7.6±0.7	-6.35	-7.82
4.82	1.13	-5.6±0.6	-6.35	-6.96

[a] Mean recoil velocity of Pt ion in Fe foil.

[b] Measured thickness of Fe foil.

[c] Predicted $\Delta\theta$ obtaing using $g(2_1^+; ^{196}Pt) = 0.326 \pm 0.014$ obtained from the weighted average of prior measurements reported in ref. 15.

[d] Obtained using the weighted mean value of experimental a_{LIN} presented in Table I.

[e] Velocity dependence of the transient field found by the authors of ref. 2 to be consistent with measurements on oxygen through samarium (see text).

Figure Caption:

Figure 1. Experimentally derived average transient field, <B>, experienced at the nuclei of Pt ions recoiling through magnetized Fe foils with mean velocities $\langle v/v_0 \rangle$. The triangular data points are those of the present work (see Table I), while the circular points represent the average transient field derived from the data of ref. 8 after appropriate normalization (see text). The straight solid line represents the weighted least-squares fit to these data of an assumed linear velocity dependence (eq. 2). The upper solid curve corresponds to the prediction of the field strength made on the basis of the "universal" parameterization of ref. 2 (eq. 1) using $v^{0.45}$ and $Z^{1.1}$. The dashed curved line represents the best $v^{0.45}$ velocity dependent least-squares fit to only the present data.

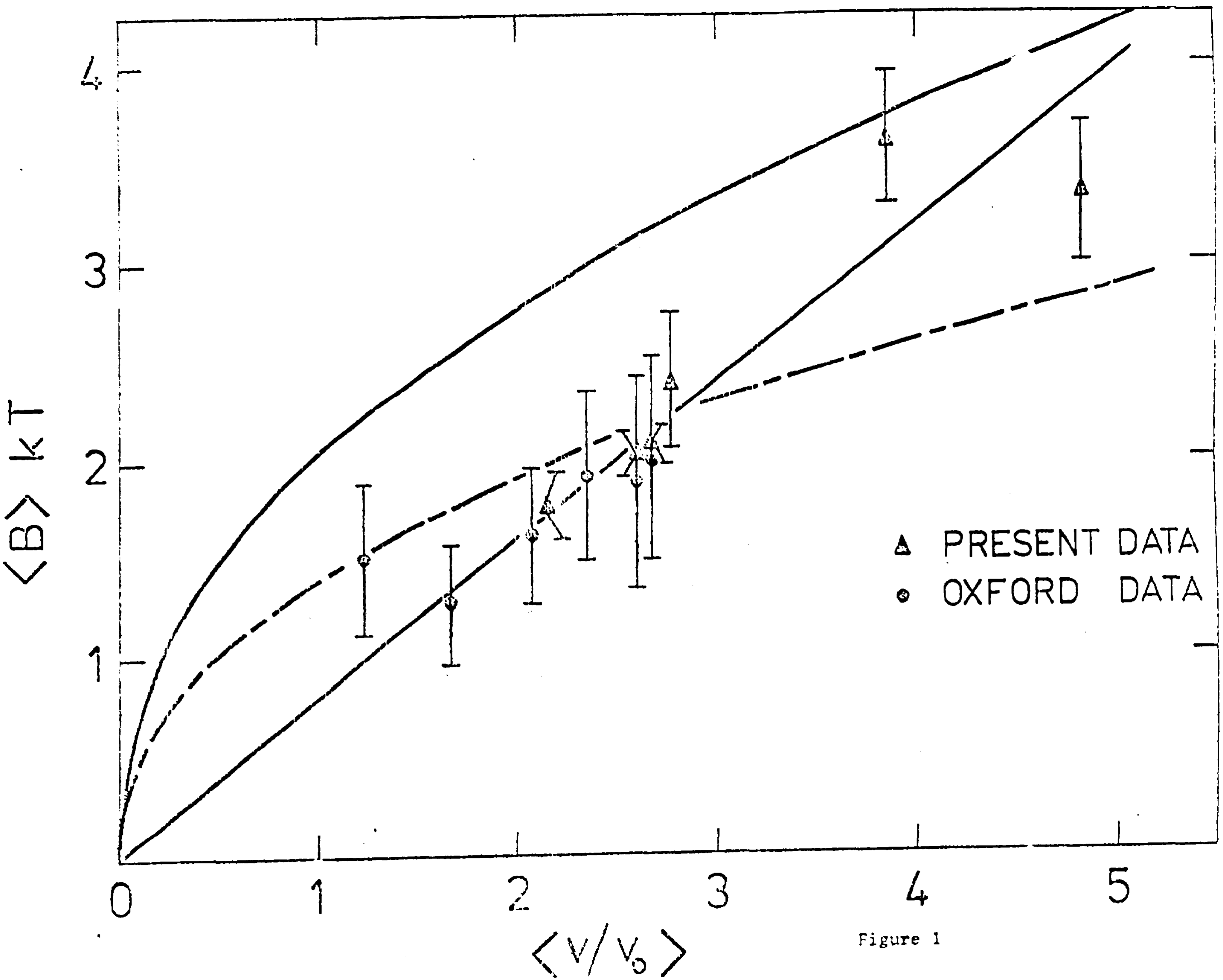

Figure 1