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# Systematics of Gyromagnetic Ratios of the $2_1^+$ States in Even Ge Isotopes

*G. J. Lampard,*[A] *H. H. Bolotin,*[A] *A. E. Stuchbery,*[A,B] *C. E. Doran*[A] *and A. P. Byrne*[A,C]

[A] School of Physics, University of Melbourne, Parkville, Vic. 3052.
[B] Department of Nuclear Physics, Research School of Physical Sciences, Australian National University, G.P.O. Box 4, Canberra, A.C.T. 2601.
[C] National Research Fellow.

*Abstract*

The relative gyromagnetic ratios of the $2_1^+$ states in $^{70,72,74,76}$Ge were measured simultaneously by means of the thin-foil, perturbed $\gamma$-ray angular distribution technique utilising the transient hyperfine field manifest at nuclei of Ge ions rapidly traversing polarised Fe. The states of interest were Coulomb excited using 75-MeV $^{34}$S projectiles incident upon a natural elemental Ge target. The present results are compared with previously reported measurements and collective model expectations.

## 1. Introduction

The gyromagnetic ratios of the first $2^+$ states in the even–even $^{70-76}$Ge isotopes have been of long-standing interest. Both the initially reported measurements (Heestand *et al.* 1969) and their subsequent reanalysis (Hubler *et al.* 1974) displayed systematic mass dependencies of the $g$-factors of these levels which disagreed markedly with that expected for these ostensibly collective states. More recently, however, the measurement of $g(2_1^+; {}^{70}\mathrm{Ge})$ by the Uppsala group (Fahlander *et al.* 1977) and their reanalysis of the earlier data set for $^{72-76}$Ge (Heestand *et al.* 1969), as well as an experimental study of the gyromagnetic ratios of the $2_1^+$ level in all four Ge isotopes by the Oxford group (Pakou *et al.* 1984), found the trend exhibited to be more in keeping with the hydrodynamical $g = Z/A$ expectation. While the findings of the former works might tend to suggest that 'anomalous' nuclear structure features could be attributed to the $2_1^+$ states of these Ge isotopes, the latter investigators indicated that such an interpretation did not appear warranted on the basis of their findings.

Nevertheless, the marked disagreement among these sets of empirical findings, together with certain differences in experimental procedures and assessments employed by these groups, have prompted us to carry out the presently reported remeasurements of the gyromagnetic ratios of the $2_1^+$ levels in $^{70,72,74,76}$Ge, utilising an experimental approach designed to obviate possible systematic problems which may have affected prior investigations.

## 2. Experimental Procedures

The $2_1^+$ states of interest in the even–even $^{70-76}$Ge isotopes were Coulomb excited using 75-MeV $^{34}$S projectiles (from the Australian National University 14 UD Pelletron

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accelerator) incident upon a natural elemental Ge target. The thin-foil, perturbed $\gamma$-ray angular distribution technique employed, utilising the transient hyperfine magnetic field manifest at the nuclei of Ge ions swiftly recoiling through a polarised Fe foil, followed that of our earlier transient field (TF) measurements of short-lived excited nuclear states (Stuchbery 1982; Stuchbery *et al.* 1985*a, b, c*; Wood *et al.* 1984, and references therein). As such, only those experimental particulars specific to the present simultaneous measurements of the *g*-factors of these states are given here.

The multi-layered target used consisted of a stratum of elemental Ge ($0 \cdot 40 \pm 0 \cdot 04$ mg cm$^{-2}$) evaporated onto one side of a $1 \cdot 83 \pm 0 \cdot 04$ mg cm$^{-2}$ (i.e. $2 \cdot 33$ $\mu$m) thick Fe foil (previously annealed in an $H_2$ atmosphere), with a $\sim 2 \cdot 7$ mg cm$^{-2}$ layer of Cu evaporated onto the other side of the Fe substrate to provide a perturbation-free environment in which the recoiling Ge ions stopped after their full traversal of the ferromagnetic foil. The laminated target was carefully pressed onto a thick Cu backing utilising a thin evaporated layer of In as an innocuous 'adhesive'. The thicknesses of the target layer substrates were determined at each stage of fabrication by both areal–weight measurements and Rutherford backscattering of 3·5-MeV protons from the University of Melbourne 5U Pelletron accelerator.

As only pure E2($2_1^+ \rightarrow 0_1^+$) transitions were of interest in the present study, near-optimal sensitivity to the nuclear precessions pertained at $\gamma$-ray detection angles of $\pm 65°$ and $\pm 115°$ to the incident beam direction (angles at which near-maximal slopes of the unperturbed $\gamma$-ray angular distributions pertained). Thus, in the precession measurements, one pair of intrinsic Ge detectors was located at $\pm 65°$ to the beam direction and another pair at $\pm 115°$. In order to match the solid angles intercepted at the target by both detectors of the forward pair, one was placed 6·7 cm from the target and the other at 6·4 cm; similarly, the target-to-detector distance of one backward-angle detector was 8·2 cm and the other 9·7 cm. The de-excitation $\gamma$ rays registered in each Ge detector were recorded in coincidence with beam ions backscattered from the Ge target layer detected in a common annular surface-barrier counter (146°–166°). Data were recorded in an event-by-event mode for Ge target ions which recoiled in a forward cone (mean half-angle $\sim 7°$), entering the Fe foil with a mean velocity of $v/c \sim 0 \cdot 042$. Thus, for all events recorded, the coincidence requirement assured both a high degree of alignment of the populated states (normal to the beam axis) and full traversal of the recoiling Ge ions through the $2 \cdot 33$ $\mu$m Fe foil before coming to rest in the perturbation-free Cu layer.

The multi-layered target was mounted between the pole pieces of an electromagnet and a polarising field of 0·05 T, sufficient to saturate the thin Fe stratum, was applied; its direction normal to the reaction plane was reversed at frequent intervals during these precession measurements to minimise possible systematic errors. A soft iron cone, positioned between the target and the annular particle detector, shielded both the incident and backscattered $^{34}S$ projectiles from the fringing field of the polarising magnet and rendered 'beam-bending' effects negligible.

## 3. Other Experimental Considerations, Data Analysis, and Results

Procedures for correction of observed TF precessions for states fed by cascade decay from higher excited states populated in the reaction, including cases in which the transit time of ions through the Fe foil is not negligible compared with level lifetimes, have been presented in our earlier publications (Wood *et al.* 1984; Stuchbery

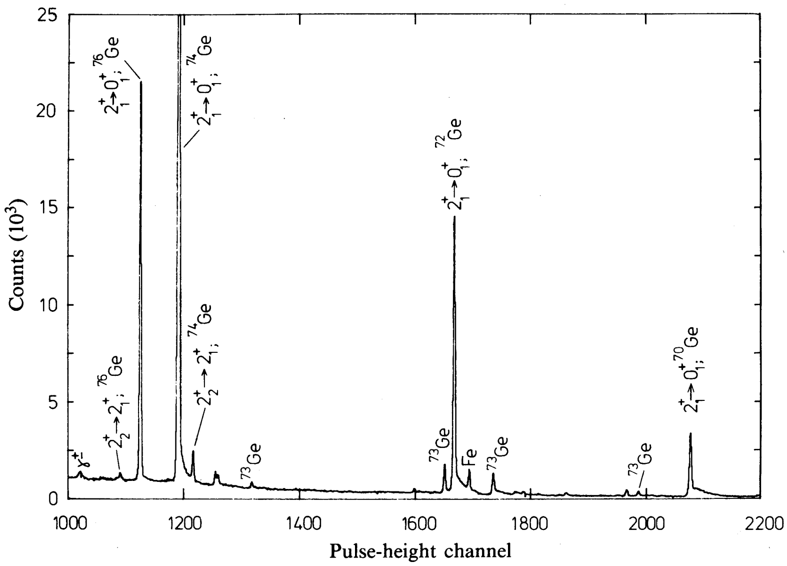


**Fig. 1.** Representative spectrum of the relevant de-excitation $\gamma$ rays detected at 65° to the beam direction in coincidence with backscattered projectiles following Coulomb excitation of levels in $^{70,72,74,76}$Ge (natural target) by 75-MeV $^{34}$S ions. Transitions are labelled by $J_i^\pi \to J_f^\pi$ and isotope. Discernible in this spectrum are small attenuated Doppler-shift shoulders on the high-energy sides of transitions from the shorter lived states which decayed as the Ge ions slowed before coming to rest in the Cu perturbation-free target backing. Chance coincidences have been subtracted. Unlabelled transitions are primarily those due to contaminant reactions.

*et al.* 1985*a, b, c*) and were employed in the present analysis. [The TF up–down asymmetry determined for each relevant de-excitation transition utilised the entire full-energy peak (including Doppler tails).] As our choice of projectile and bombarding energy in the present measurement resulted in states higher than the $2_1^+$ levels being only weakly populated, corrections for feeding were very small. The relevant portion of the $\gamma$-ray spectrum recorded in one of the forward intrinsic Ge detectors in coincidence with backscattered projectile ions is presented in Fig. 1. Corrections for decays-in-transit were also small ($\leqslant 7\%$), even for the shortest lived state of interest ($\tau = 1\cdot 88$ ps for the $2_1^+$ level in $^{70}$Ge). The smallness of these corrections preserved the virtual independence and insensitivity of our corrected precessions to the specifics of the parametrisations employed (Shu *et al.* 1980; Andrews *et al.* 1982) for the velocity dependence of the TF strength for Ge ions traversing the Fe foil and to the lifetimes of these $2_1^+$ states.

Our experience (Stuchbery *et al.* 1985*a, b, c*) has been that unperturbed angular distributions of de-excitation $\gamma$ rays from $2_1^+$ states can be calculated with confidence and reliability when, as is the present case, there is only comparatively weak population of higher states. This was done using the Coulomb excitation code (Winther *et al.* 1966) to obtain the alignment tensors for the geometric arrangement of the annular particle detector employed in the present work. Relevant E2 matrix elements were obtained from the findings of earlier investigators (Kocher 1976; Kearns and Mo 1978, 1980; Singh and Viggars 1984). Finite solid-angle attenuation factors for the

$\gamma$-ray detectors were obtained in a manner similar to that given by Krane (1973). The logarithmic derivatives of the unperturbed $\gamma$-ray angular distributions calculated were then used to extract the relative TF precessions from the measured up–down TF asymmetries for all states of interest.

It should be noted that the present results yield only the *relative* gyromagnetic ratios of the $2_1^+$ states in these four Ge isotopes. To infer the *absolute* $g$-factors of each of these levels requires normalisation of the integrated TF strength (common to all of the Ge isotopes in the present simultaneous measurement of the precessions of the $2_1^+$ states), relying on the known, previously determined, $g$-factor of any one of the levels investigated. However, as the present work was undertaken, at least in part, to more systematically and reliably determine these gyromagnetic ratios, adoption of any one of these previously inferred $g$-factors to affect a 'definitive' TF strength calibration would tend to restrictively bias the present, otherwise independent, findings. Instead, the absolute gyromagnetic ratios were inferred from these relative $2_1^+$ state precessions using the average of the time-integrated TF strengths obtained from the velocity-dependent TF parametrisations of the Rutgers (Shu *et al.* 1980) and Chalk River (Andrews *et al.* 1982) groups. Although the latter parametrisation was based upon empirical data for the rare-earth nuclides ($150 \leqslant A \leqslant 174$), and the former primarily for the $A \leqslant 150$ isotopes, these two parametrisations yield quite similar projected TF strengths in both mass ranges. In the present case, the two parametrisations yielded integrated TF strengths for the Ge isotopes which differed by ~5%, with the Rutgers form yielding the slightly lower value. Account was taken in these evaluations of the TF strengths of slight differences in the reaction kinematics for the four Ge isotopes.

**Table 1. Experimental particulars and results of measured $g$-factors for $2_1^+$ states in $^{70-76}$Ge**

| Ge isotope[A] | Level energy (MeV) | Mean life[B] (ps) | $T_{Fe}$[C] (ps) | $E_i$[C] (MeV) | $E_e$[C] (MeV) | $\langle v/v_0 \rangle$[C] | $\langle \Delta\theta \rangle$[D] (mrad) | Gyromagnetic ratios Present[E] | Oxford[F] |
|---|---|---|---|---|---|---|---|---|---|
| 70 | 1·040 | 1·88 | 0·23 | 61 | 22 | 4·6 | −6·0(14) | 0·370(89) | 0·468(26) |
| 72 | 0·834 | 4·76 | 0·24 | 61 | 21 | 4·5 | −6·4(8) | 0·367(44) | 0·399(33) |
| 74 | 0·596 | 18·8 | 0·24 | 60 | 21 | 4·4 | −6·24(39) | 0·350(22) | 0·433(20) |
| 76 | 0·563 | 25·2 | 0·25 | 59 | 21 | 4·3 | −5·9(7) | 0·334(39) | 0·419(23) |

[A] Isotopic abundance of natural Ge: $^{70}$Ge(20·7%), $^{72}$Ge(27·5%), $^{73}$Ge(7·7%), $^{74}$Ge(36·4%) and $^{76}$Ge(7·7%).
[B] Mean lives of $2_1^+$ states (Lecomte *et al.* 1980*a*, 1980*b*).
[C] Mean transit time of recoiling Ge ions through Fe foil, $T_{Fe}$, mean energy of ions incident upon $E_i$, and emergent from $E_e$, the Fe foil, and mean velocity of ions, $\langle v/v_0 \rangle$, in Fe foil were obtained using the known target and Fe foil thicknesses, the reaction kinematics, and the stopping powers by Ziegler (1977). Bohr velocity $v_0$ is $c/137$.
[D] Measured precession angles uncorrected for decay-in-transit.
[E] Present inferred (positive) $g$-factors of levels after very small corrections for decay-in-transit using the mean of the integrated TF strengths for Ge recoiling through Fe parametrised by the Rutgers (Shu *et al.* 1980) and Chalk River (Andrews *et al.* 1982) groups (see Section 3). The uncertainties specified for the present inferred absolute $g$-factors are experimental only; any slight modification of the adopted integrated TF strength which might later be justified would simply alter all listed present $g$-factors by the same minor degree.
[F] The (positive) $g$-factors inferred by the Oxford group (Pakou *et al.* 1984) utilised the Rutgers (Shu *et al.* 1980) TF parametrisation.

Table 1 presents the results of the present study, some related experimental particulars, and a comparison of the present inferred absolute $g$-factors with those of the Oxford group (Pakou *et al.* 1984). These results are compared in Fig. 2 with those of the earliest workers (Heestand *et al.* 1969), with the reanalysis of these same data by the Uppsala group (Fahlander *et al.* 1977), and with the collective $Z/A$ estimate. The marked departures of both the original data set and its reanalysis from the hydrodynamical expectation for the *mass dependence* of $g(2_1^+)$ in these even Ge isotopes is evident; departures which suggested possible 'anomalous' nuclear structure features might be attributed to the first-excited states of these even–even Ge isotopes.

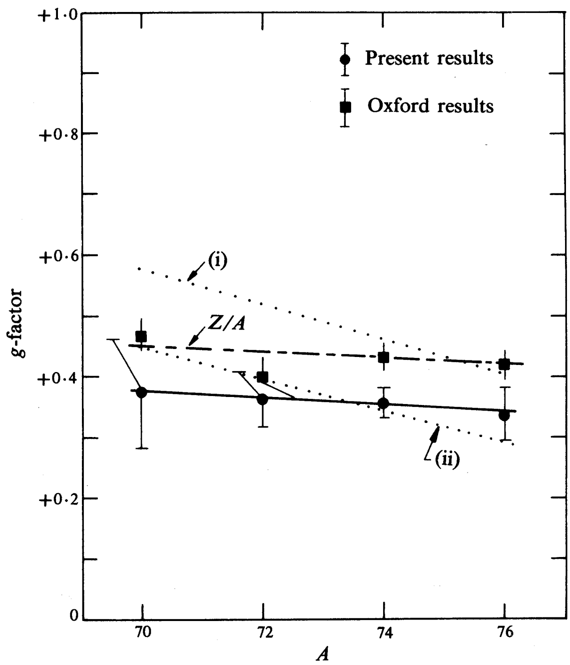


**Fig. 2.** Present and previously reported inferred gyromagnetic ratios of $2_1^+$ states in the even $^{70-76}$Ge isotopes plotted as a function of isotopic mass. The linear least-squares fit to the present data is given by the solid line and $g = Z/A$ by the dashed line; dotted lines represent the mass dependencies of (i) the results of Heestand *et al.* (1969) and (ii) these results as reanalysed by Fahlander *et al.* (1977).

Although the mass-dependence trend found for these gyromagnetic ratios matches the $g$ versus $A$ slope of the $g = Z/A$ expectation in both the present and Oxford (Pakou *et al.* 1984) works, our inferred absolute $g$-factors are $\sim$20% lower than the strict $g = Z/A$ estimate, while those of Pakou *et al.* are virtually identical with it. It is clear in the present study, however, that as we employed the arithmetic mean of the integrated TF strengths obtained on the basis of the Rutgers (Shu *et al.* 1980) and Chalk River (Andrews *et al.* 1982) field parametrisations (the former is $\sim$5% smaller than the latter) to infer the absolute $g$-factors, exclusive use of one or the other of these parametrisation forms would have only served to raise or lower all the values of our quoted gyromagnetic ratios by $\sim 2 \cdot 5\%$; far too small to account for our inferred $g$-factors being $\sim 20\%$ lower than both the $Z/A$ expectation and the Oxford results. Inspection of the tabulated gyromagnetic ratios measured for the $2_1^+$ states of nuclides in this mass region (Lederer and Shirley 1978) also displays a 'quenching' of these $g$-factors relative to $g = Z/A$, in keeping with the present findings.

While it is difficult to attribute with certainty the reasons for the $\sim 20\%$ difference between the present inferred $g$-factors and those reported by the Oxford group, it is worth noting the differences in the experimental procedures employed. The present findings were obtained in a single simultaneous measurement of the relative $g$-factors of these states using one target, while Pakou *et al.* (1984) employed six different targets, each consisting of pairs of isotopes,, mounted on six Fe foils of different thicknesses. Further, as the present investigation employed intrinsic Ge $\gamma$-ray detectors in the precession measurements, we were able to resolve the weak $2_2^+ \rightarrow 2_1^+$ (608 keV) transition from the $2_1^+ \rightarrow 0_1^+$ (596 keV) line in $^{74}$Ge; as well, the weak, but ubiquitous, 847-keV transition from the Coulomb-excited $2_1^+$ state in Fe was resolved from the $2_1^+ \rightarrow 0_1^+$ (834 keV) $\gamma$ ray in $^{72}$Ge in our spectrum (Fig. 1). Although Pakou *et al.* employed a single Ge detector as a monitor in which each line of these transition pairs would have been separated, such would not have been the case in their precession measurement spectra recorded with four NaI detectors. Any difficulties or systematic uncertainties which may have resulted from the required NaI spectra 'stripping' or 'unfolding' procedures used in their analyses of their precession data might have contributed, to some degree, to the differences between their results and ours. As well, it is also possible that the 'small dip' in their measured $g(2_1^+; {}^{72}\mathrm{Ge})$ value and their inferred absolute $g$-factor of the $2_2^+$ state in $^{74}$Ge [which they discussed briefly in terms of possible 'forbidden' M1 transition strength between the $2_2^+$ (two-phonon) and $2_1^+$ (one-phonon) levels] may have been affected, in part, by NaI spectra analysis procedures. While one can only speculate on possible causes of the discrepancies between the present and Oxford results, the foregoing does serve to summarise the more obvious differences between these two experimental methods.

## 4. Discussion

The present measured transient field precessions and inferred gyromagnetic ratios of the $2_1^+$ states in the even–even $^{70-76}$Ge isotopes are consistent with the expectations of the hydrodynamical model; the observed mass dependence of these $g$-factors is in excellent agreement with that given by the collective $g = Z/A$ dependence. While the inferred absolute values of $g(2_1^+)$ obtained in the present work for these isotopes are $\sim 20\%$ lower than the $Z/A$ estimate, such a reduction is more the norm in this mass region than is the virtual equality with $g = Z/A$ obtained by the Oxford group (Pakou *et al.* 1984); see Fig. 2. Indeed, the measurement of $g(2_1^+; {}^{70}\mathrm{Ge}) = 0 \cdot 38 \pm 0 \cdot 08$ obtained by the Uppsala workers (Fahlander *et al.* 1977), when coupled with their reanalysis of the earlier data (Heestand *et al.* 1969) for $g(2_1^+)$ in $^{72,74,76}$Ge, appears more in keeping with the present findings than those of the Oxford group. [It may be of interest in this regard that an early estimate of the 'quenching' of $g$-factors relative to that of the expected $Z/A$ value (Greiner 1966) for vibrational nuclei (using standard pairing parameters) predicts the gyromagnetic ratios of the $2_1^+$ levels in these even Ge isotopes to be reduced even more than found empirically in the present work (i.e. $\leqslant 0 \cdot 7$ of the $g = Z/A$ value).] Nevertheless, the salient point is that the present findings do not warrant any suggestion of 'anomalous' nuclear structure characteristics in the make-up of these $2_1^+$ states in the even Ge isotopes; the measured gyromagnetic ratios and other features already determined for these first excited states appear wholly consistent with collective model expectations.

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