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The g-factors of the first 2^+ states in ^{50,54}Cr, ^{54}Fe and ^{70}Ge

by

C. Fahlander, K. Johansson, E. Karlsson
and G. Possnert
Institute of Physics, University of
Uppsala, Box 530, S-751 21 Uppsala,
Sweden

UUIP-965 April 1977

Abstract

The gyromagnetic ratios of the first excited $J^\pi = 2^+$ states of ^{50,54}Cr, ^{54}Fe and ^{70}Ge have been determined by the ion-implantation perturbed angular correlation technique (IMPAC) with ferromagnetic Gd as stopping material. The deduced values are 0.52±0.11, 0.49±0.11, 1.24±0.34 and 0.44±0.17, respectively. With the exception of ^{54}Fe all g-factors are close to the collective value. A re-evaluation of earlier IMPAC data on ^{70,72,74,76}Ge with Fe as stopping material has been performed. The value obtained for ^{70}Ge is in good agreement with the one measured in this work.

SW ISSN 0042-0263

Introduction

The magnetic moments of the lowest 2^+ states in spherical or nearly spherical even-even nuclei are already known with reasonable accuracy in some regions of the nuclear chart. The g-factors show, in general, very little variation and most of the data are consistent with the simple hydrodynamical estimate for collective motion, $g = Z/A$ in contrast to the quadrupole moments which vary systematically for the same type of nuclear states. Because of the insensitivity to the microscopic structure further g-factor measurements may seem of limited value, unless they can be made with much higher precision than now. There are, however, some groups of nuclei where the g-factors of the 2^+ levels may still provide basic information about the excitation processes, namely those with closed or nearly closed shells for protons or neutrons.

The 2^+ states near shell closures lie in general fairly high up in energy and are short-lived (with life-times around 1 ps). They are therefore accessible to measurement only with very special experimental arrangements where the method used (IMPAC) is pushed to its extreme limits of application. It is only after the selection of an optimum ferromagnetic stopping material and careful studies of the behaviour of the transient magnetic fields that reliable nuclear g-factors can be derived from the method. After having performed such investigations on ferromagnetic gadolinium [1] we have applied the IMPAC method to four cases in the A = 50-70 range.

The three first nuclei studied are situated close to the ^{56}Ni (Z=28, N=28) core, whereas the fourth is the case of ^{70}Ge, which has been discussed in terms of possible effects of a neutron sub-shell gap at N=38. We have remeasured the case of ^{54}Fe (Z=26, N=28), which has been reported to have a high nuclear g-value from IMPAC-experiments in iron, and also studied the cases of ^{50}Cr (Z=24, N=26) and

^{54}Cr (Z=24, N=30), where only two proton pairs and one neutron pair are expected to be active in producing the 2^+ states. The case of ^{70}Ge is also a redetermination, since we found it doubtful that the assumptions earlier assumed for the transient field could be extended to such a very short-lived state (τ = 1.88 ps).

Experimental technique and analysis

The measurements reported in this paper have been performed with the ion-implantation perturbed angular correlation technique (IMPAC) [2,3]. A heavy ion beam was used to Coulomb excite and subsequently recoil implant the nucleus under study into ferromagnetic Gd. The excited nucleus will experience a large transient magnetic field B_{tr} during the slowing down time ($t_s \sim 2$ ps) and a static hyperfine field after coming to rest. Although the lifetime of the excited state may be short ($\tau \sim 10^{-12}$ s) a measurable precession will be achieved due to the large magnitude (several MGauss) of B_{tr} [1,4].

The experiments were performed using beams of 36 MeV $^{16}O^{6+}$ ions accelerated in the EN tandem Van de Graaff accelerator in Uppsala. In order to reduce radiation damage and heating effects the beam current never exceeded 50 nA. Backscattered particles, detected in an annular surface barrier detector, were measured in coincidence with γ-rays detected in four 3"x3" NaI detectors. The γ-detectors were placed 10 cm from the target in the plane perpendicular to the external field. The electronic system based on the usual fast-slow coincident arrangement allowed real and random collection of γ-ray coincidences. The external magnetic field was automatically reversed after a preset amount of $2 \cdot 10^6$ particles in the particle window.

The targets were prepared from isotopically enriched material and evaporated onto a Gd-In-Cu sandwich backing. Since the Curie temperature of Gd is 293 K the foils have to be cooled in order to become ferromagnetic. The In layer ensured good thermal contact between the copper heat sink and the Gd foil. The targets were therefore mounted onto a cold finger (~ 80 K) and placed in the polarizing magnetic field of 3.1 kG.

The angular shifts $\Delta\theta$ were extracted from the ratio

$$R = \frac{C(\theta, +B) - C(\theta, -B)}{C(\theta, +B) + C(\theta, -B)}$$

and the relation

$$R \approx \frac{1}{W}\frac{dW}{d\theta}(\Delta\theta)$$

W is the time integral angular correlation function and $C(\theta, \pm B)$ are the integrated photopeak areas accumulated for external field up and down. The γ-detectors were positioned on the maximum slope of $W(\theta)$ at angles $\theta = \pm 25^{\circ}$ and $\theta = \pm 115^{\circ}$. The extracted angular shifts were corrected for small beam bending effects.

Results

For lifetimes of excited states less than a few ps, the precession of the magnetic dipole moments in the transient field may be greater than the precession in the static hyperfine field. This is especially the case for ions recoiling into Gd where the static hyperfine field in many cases can be neglected. The g-factor of the excited state may then be obtained from the transient precession angle (φ) provided a reliable calibration of the reduced transient shift (φ/g) exists for recoiling ions of the same kind.

Systematic studies for Gd as stopping medium have recently been reported [1] where the dependence of B_{tr} on the velocity and atomic number Z_1 of the recoiling ions was investigated. The result was consistent with a directly proportional velocity dependence in contradiction to the Lindhard and Winther theory [5]. Using the empirical formula

$$B(v) = a\ R\ Z_1 \left(\frac{v}{v_o}\right)^P \qquad (1)$$

given by Eberhardt et al. [6], with p=1 and the parameter a = 12.6±0.6 T it was possible to reproduce all the available experimental data in Gd. This systematic behaviour of the reduced transient shift is used in the present work for determination of g-factors.

The transient shift $\varphi(\tau)$ is given by Lindhard and Winther [5] as

$$\varphi(\tau) = g \frac{\mu_N}{\hbar} A_1 M \int_0^v \frac{B(v) e^{-t(v)/\tau}}{dE/dR} dv \qquad (2)$$

where A_1M is the mass of the moving ion, and dE/dR is the stopping power of the backing material. The relation t(v) is taken from a stopping power calculation for each particular ion in gadolinium and the exponential factor corrects for decay in flight.

The quantity $\varphi(\tau)/g$ is independent of the nuclear magnetic properties. Fig. 1 shows the reduced transient shift for the case of Fe ions stopping in Gd calculated for the empirically found linear velocity dependence (solid lines) and with B(v) according to the adjusted Lindhard-Winther theory [4,7] (dotted lines). By comparing the curves for τ = 10 ps and τ = 1 ps it is seen that $\varphi(\tau)/g$ is not so much reduced by decay in flight when the velocity dependence is linear as it is in the LW-theory. The linear B(v) relation is therefore favourable in g-factor measurements of very short-lived nuclear states.

The reported g-factors were deduced from the total precession

$$\Delta\theta = \varphi(\tau) - \frac{\mu_N}{\hbar} g\, B_o\, \tau e^{-t_s/\tau}$$

$$= g \frac{\mu_N}{\hbar} \left\{ A_1 M \int_o^v \frac{aRZ_1 (\frac{v}{v_o}) \cdot e^{-t(v)/\tau}}{dE/dR} dv - B_o\, e^{-t_s/\tau} \right\} \qquad (3)$$

In the last term, which is the precession in the static hyperfine field B_o, the exponential factor corrects for the fact that this field acts only on nuclei which remain excited after the stopping time t_s. The experimentally determined total angular shifts, $\Delta\theta_{exp}$, together with the parameters necessary for the evaluation of the g-factors are presented in Table 1 for the investigated nuclei.

$^{50,54}Cr$

The run sequence for the two Cr isotopes are displayed in Fig. 2. Each experimental point represents about 6 h of effective beam time. The g-factors were deduced to be 0.52±0.11 and 0.49±0.11 for ^{50}Cr and ^{54}Cr respectively. In the evaluation of these g-factors a value of B_0= +23.1±5.4 kGauss was taken from ref. 8. The value of φ/g = 57±15 mrad was taken to be the same as that of ^{56}Fe recoiling into Gd [1]. This is reasonable since the atomic number of Cr and Fe are close and the recoil velocities are almost the same. The correction of the reduced transient shift for decay in flight can be neglected since the lifetimes of ^{50}Cr and ^{54}Cr are 13.3 ps and 11.6 ps respectively.

^{54}Fe

The g-factor of the short-lived 1.408 MeV 2^+ state of ^{54}Fe was determined to be 1.24±0.34. The reduced transient shift was taken from the ^{56}Fe data and corrected for decay in flight [1]. From a Mössbauer measurement a static hyperfine field for FeGd of 0±16 kGauss has been achieved [8].

The 1.369 MeV γ-peak from the reaction $^{16}O(^{12}C\alpha)^{24}Mg$ can not be resolved from the close lying iron peak (1.408 MeV) by a NaI detector and might be a problem since the excitation yield of ^{54}Fe is comparatively low. A coincidence measurement with a Ge(Li) detector showed, however, that the γ-rays from this reaction had no influence. This was furthermore confirmed by routing the particles with a γ-gate in the NaI spectrum. Particles backscattered from ^{54}Fe formed a peak well separated from the low energetic α-particle distribution.

^{70}Ge

For the shortlived (τ = 1.88 ps) 2^+ state of ^{70}Ge the reduced transient shift $\varphi/g = 49\pm18$ mrad was taken from the systematics in ref. 1. The static hyperfine field for Ge<u>Gd</u> is not known. This is, however, of minor importance since the short lifetime implies that the precession in the staic field is negligible. Our value $g = 0.44\pm0.17$ is in contradiction to the result of Hubler et al. [7] who reported a twice as large value. Their measurement was performed in Fe using the earlier accepted assumption about the velocity dependence of the transient magnetic field.

Re-evaluation of published g-factors of $^{70,72,74,76}Ge$

In the light of the linear velocity dependence found for the transient field in Fe [6] it was of interest to re-evaluate published data for the Ge isotopes. In this case one can not neglect the contribution from the static field. A value of $B_0 = 7.0\pm0.3$ T [9] was used. The measured total shifts were taken from Hubler et al. [7] and the reduced transient shift $\varphi/g = -26.9\pm5.8$ mrad was obtained from the systematics in the same reference. Since the new velocity dependence is less sensitive for decay in flight (see Fig. 1) the earlier reported g-factors are reduced, especially for the shortlived isotopes. The g-factors deduced for the Ge isotopes together with the values reported in ref. 7 are presented in Table 2. The re-evaluated g-factor of ^{70}Ge is consistent with that found in the present measurement.

Discussion

Our result for ^{54}Fe (2^+) is in agreement with that of Hubler et al. [7] who reported a g-factor of 1.43±.28. It is also in excellent agreement with the theoretical prediction by Zamick [10] who assumed the state to arise from a simple $(f^2_{7/2})2^+$ coupling of the two proton holes and assumed that the magnetic moment of a single $f_{7/2}$ proton hole is the same as that measured for the ground state of ^{55}Co (μ = 4.2 nm). This assumption leads to g = 1.2 for the 2^+ state. It was also discussed by Zamick whether this effective single particle moment could be used when two holes are present, since it is known that the reduction from the single particle value is caused by polarization of the core and the effects of two particles (or holes) may not be additive. The more detailed treatments using perturbation theory or matrix diagonalization showed, however, that the effective moment should rather increase the effective moment than lower it and led to predictions of about g = 1.4 for ^{54}Fe(2^+). Our result can not confirm these finer details of the theory but it seems to be no doubt that the 2^+ state in ^{54}Fe is essentially of two-hole excitation of protons in $f_{7/2}$ states.

The 2^+ states in ^{50}Cr and ^{54}Cr have two neutrons outside the closed shell in addition to the four protons and the situation becomes more complicated. The case of ^{54}Cr has been discussed by Bhatt et al. [11]. They considered valence protons in the $0f_{7/2}$ and neutrons in the $1p_{3/2}$, $1p_{1/2}$ and $0f_{5/2}$ orbits and made shell-model calculations with effective p-p, n-n and n-p interactions taken to fit the observed energy spectra in ^{54}Fe, ^{58}Ni and ^{49}Ca, respectively. It could be shown that such calculations rapidly lead to a high degree of collectivity in the even-even nuclei when the number of valence particles or holes are increased up to six. The low lying states of ^{54}Cr (Z = 24, N = 30) are clearly more collective than those of ^{56}Fe (Z = 26, N = 30) and the quadrupole operator connects the calculated 2^+ states very strongly with the 0^+ ground states. In a work on $^{50,52,54}Cr$ by Towsley et al. [12] the quadrupole moments were measured and discussed in terms of configuration mixings involving the same shell model states as above. The quadrupole moments of $^{50,52}Cr$ could be adequately described by a strong mixing of states involving excitations to $p_{3/2}$ and $f_{5/2}$ orbits, while for ^{54}Cr it seemed necessary also to include higher lying neutron single particle states. Information on the single-particle strengths in the 2^+ state of ^{54}Cr can also be obtained from the spectroscopic factors measured in $^{53}Cr(d,p)$ ^{54}Cr reactions [13]. A recent calculation has been reported by Sharma [14] who could reproduce the quasi-rotational character of the ^{50}Cr states by a shell model calculation. Unfortunately, this paper contains no predictions for the magnetic moments of the excited states.

The present experimental results for the 2^+ states of ^{50}Cr and ^{54}Cr are in agreement with the values expected for a completely collective excitation. This is therefore another experimental support for the high degree of collectivity suggested by the theory and other types of experiments for the low-lying states of these nuclei.

The isotope ^{70}Ge (Z = 32, N = 38) has been suggested to be a case of neutron sub-shell closure since the $1f_{5/2}$-$2p_{1/2}$ energy difference seems to be of the order of 2-3 MeV [15]. Full scale shell-model calculations have not been reported, because of the large number of particles and available states. Measured filling coefficients V_j^2 for the $2p_{3/2}$ and $1f_{5/2}$ neutron levels are fairly high ($\approx$ 0.8) while the occupation probability for the $2p_{1/2}$ and $1g_{9/2}$ levels are small. The reported measurement of the 2^+ g-factor of ^{70}Ge [7] was

0.88±0.21, which raised the question whether ^{70}Ge (2^+) could be regarded as a few-particle excitation.

The measurement reported here, g = 0.44±0.17 is in sharp contrast to the earlier value and suggests that the 2^+ excitation in ^{70}Ge and the other Ge-isotopes is also collective, which is not surprising in view of the four active protons and the remaining excitation probabilities for the neutrons.

Acknowledgements

The authors are indebted to Prof. A. Johansson and the staff at the tandem laboratory for placing good research facilities to their disposal.

Mr L. Einarsson and Mr J. Kjellberg are gratefully thanked for the target preparation.

This work was financially supported by the Swedish Council for Atomic Research.

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Table captions

Table 1. Experimental results for $^{50,54}Cr$, ^{54}Fe and ^{70}Ge implanted into ferromagnetic Gd.

Table 2. Re-evaluated g-factors of $^{70-76}Ge$ from data given in ref. 7.

Figure captions

Fig. 1. Theoretical calculations of reduced transient shifts for ^{54}Fe recoiling into Gd at different energies and with assumed lifetimes of 1 ps and 10 ps. The solid line (emp) is calculated using the empirical formula of B(v) (eq. 1). The dotted line (ALW) corresponds to calculations within the Lindhard and Winther model and with the adjusted parameters $v_p = 0.18\ v_o$ and $C = 1.0$ taken from ref. 4.

Fig. 2. Run sequence for ^{50}Cr and ^{54}Cr.

Table 1.

Nucl	2^+ keV	E_R MeV	τ ps	t_s ps	B_o a) kGauss	$-\Delta\theta$ mrad	$-\varphi/g$ b) mrad	g
^{50}Cr	783	26.4	13.3±0.5	2.46	+23.1±5.4	30.5±2.4	57±15	0.52±0.11
^{54}Cr	835	25.4	11.6±0.2	2.44	+23.1±5.4	28.4±1.4	57±15	0.49±0.11
^{54}Fe	1408	24.7	1.15±0.04	2.36	0±16	32.4±2.3	57±15	1.24±0.34
^{70}Ge	1040	21.4	1.88±0.04	2.14		16.2±1.8	49±18	0.44±0.17

a) ref. 8.

b) ref. 1.

Table 2.

Nucl	2^+ keV	τ ps	E_R MeV	B_o a) kGauss	$-\varphi/g$ b) mrad	$-\Delta\theta$ b) mrad	g ref. b	g recalculated
^{70}Ge	1408	1.88±0.04	21.4	+70±3	26.9±5.8	11.2±1.5	0.88±0.21	0.48±0.12
^{72}Ge	834	4.76±0.58	21.4	+70±3	26.9±5.8	9.9±1.7	0.58±0.14	0.37±0.10
^{74}Ge	596	18.80±0.29	21.4	+70±3	26.9±5.8	11.3±1.3	0.47±0.10	0.35±0.08
^{76}Ge	563	25.2±0.26	21.4	+70±3	26.9±5.8	9.9±1.5	0.36±0.08	0.28±0.07

a) ref. 9.

b) ref. 7.

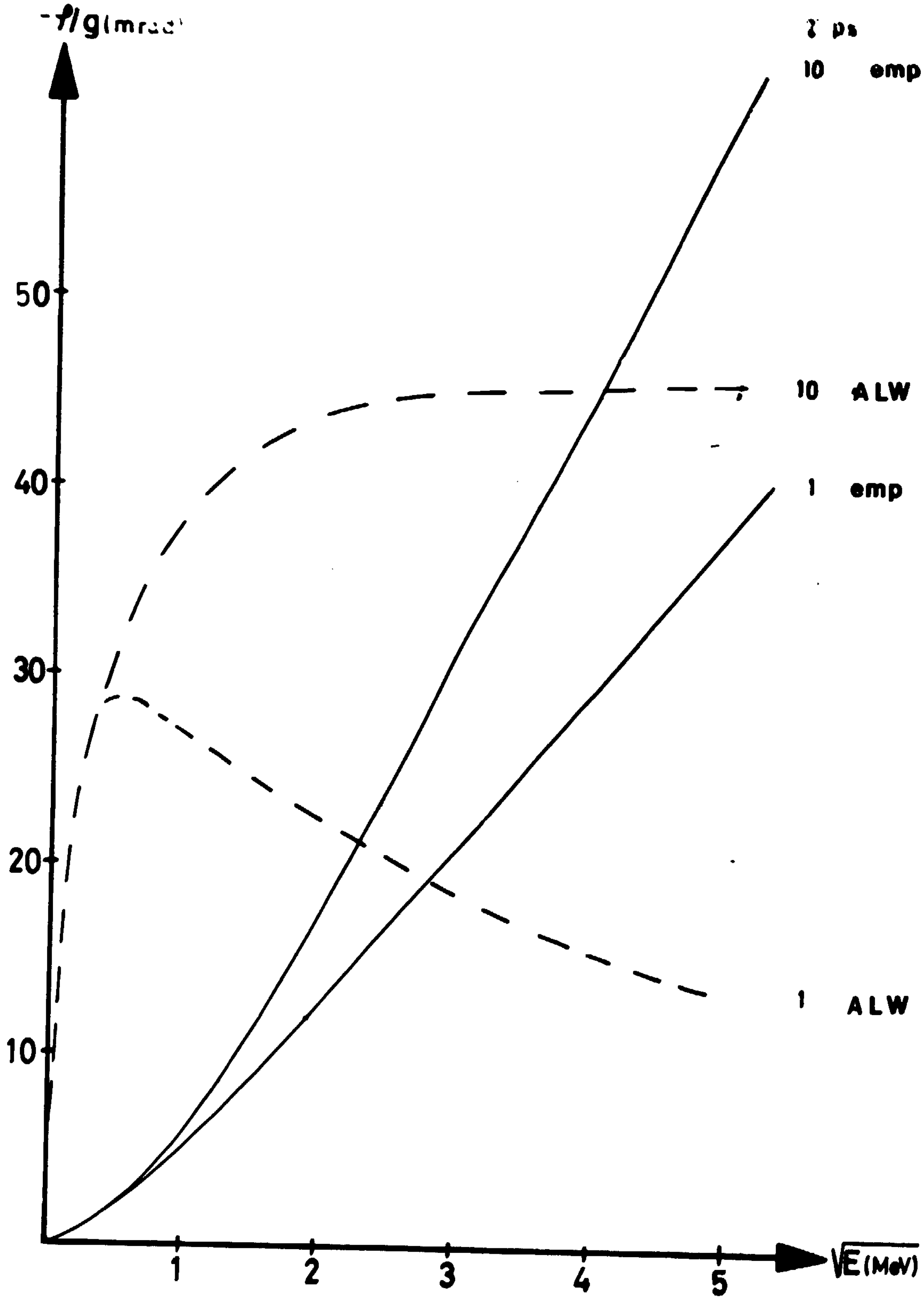

FIG 1

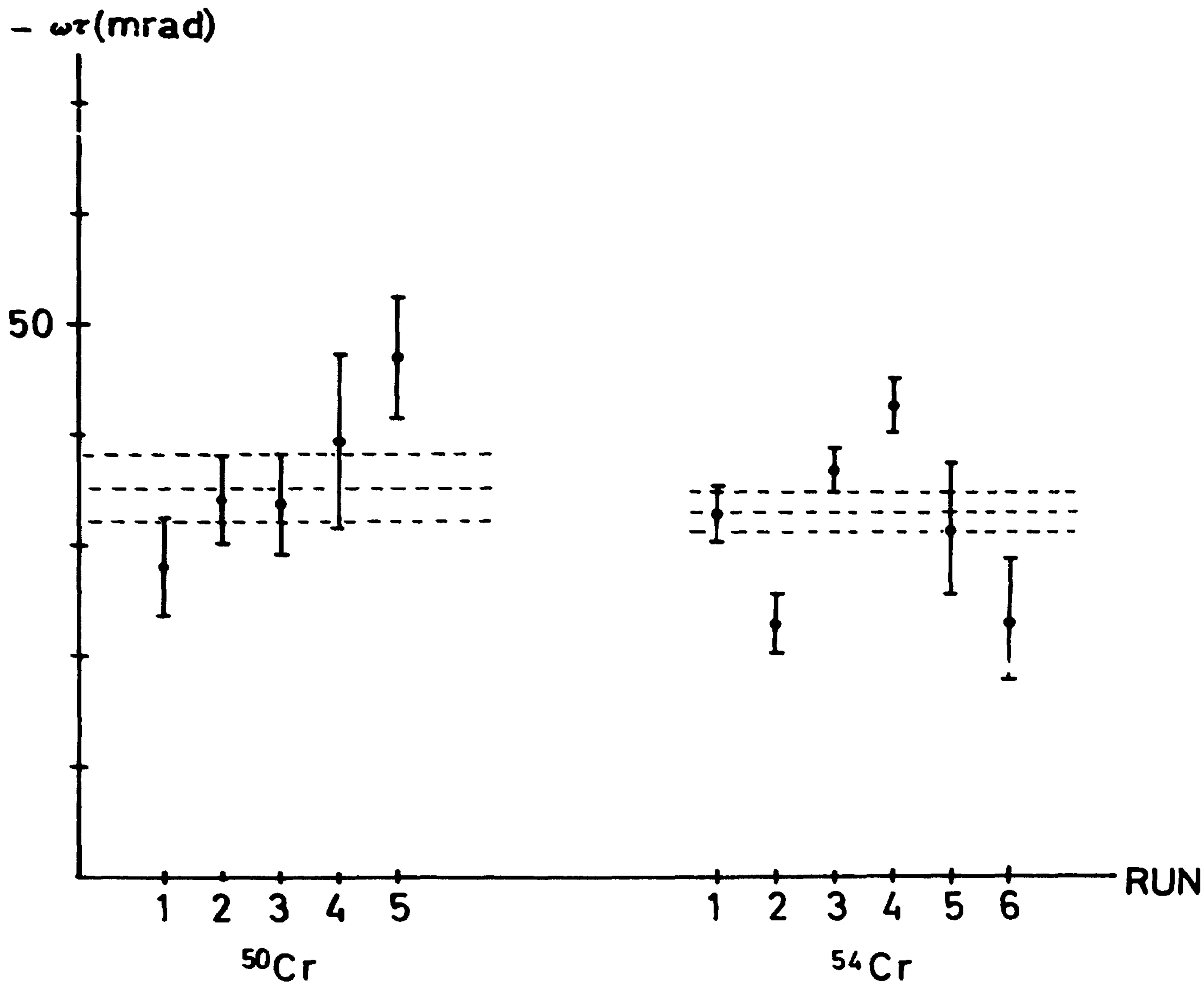

FIG 2