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II.c. Magnetic Moments of Short-Lived States by Use of a Stopper in the Recoil-into-Gas Method

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(Presented by S. S. Hanna)

Measurements of magnetic dipole moments of very short-lived states have been performed with the recoil-into-gas method. A stopper is used to control the flight time of the recoils and hence the time during which the hyperfine perturbation is applied. The hyperfine fields are calibrated by use of nuclear states with known g-factors. Results for the $3/2^-$ and $5/2^-$ levels of ^{103}Rh, ^{107}Ag, and ^{109}Ag are compared with the core-excitation model.

The basic method used in this investigation is illustrated in Fig. 1. A ^{35}Cl beam with energy in the range 60–80 MeV strikes a thin target containing the desired nuclei and excites

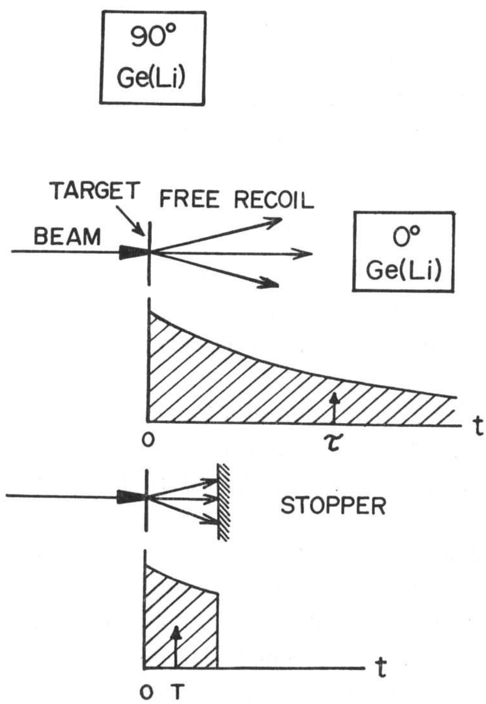

Fig. 1. Method of recoil-into-gas with a stopper to control the perturbation time.

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and ejects them into a vacuum space behind the target. The Coulomb excitation process aligns the nuclei in the highly ionized recoil ions and the hyperfine interaction in the ion ($\sim 10^8$G) subsequently perturbs the alignment. The amount of alignment present in a given case is determined by measuring the angular distribution of the emitted γ-rays by either of two techniques:

(1) *Ratio method*: the γ-ray yields at 0° and 90° (or any two desired angles) are measured with two fixed detectors (usually Ge) and the ratio of the yields is used to measure the degree of nuclear alignment.

(2) *Line shape analysis*: the recoil-γ-ray angular correlation produces a characteristic line shape for γ-rays emitted at 90° (or any other angle) and the change in this line shape is used as a sensitive measure of the change in the γ-ray angular correlation.

The hyperfine interaction term $\omega = \mu H$ can be determined by two methods:

(1) *Gas method*:[1] gas is introduced in the space traversed by the recoils. Collisions with the gas molecules cause the hyperfine field H to fluctuate randomly in direction. As the gas pressure is increased the collision time decreases and the average hyperfine field decreases and eventually vanishes. The perturbation measured as a function of gas pressure can be analyzed with either of the following theories,

(a) Abragam-Pound (AP):[2] if the time between collisions, characterized by the correlation time τ_c, is short compared to the time during which the perturbation is applied, as given by the lifetime τ for free recoil, then the perturbation parameter G_2 which multiplies $P_2(\cos\theta)$ in the angular correlation function is given by

$$G_2 = \frac{1}{1 + 2\omega^2\tau\tau_c}\,.$$

(b) Scherer-Blume (SB):[3] this theory is equivalent to the AP theory for short correlation times but may also be used for long correlation times out to infinity, *i.e.* for static perturbations. In this case however the perturbation necessarily depends on the angular momentum of the ion.

(2) *Decoupling field*:[4] by application of a longitudinal field the nuclear moment can be decoupled from the hyperfine field. By determining the amount of decoupling as a function of the field strength, the interaction μH can be determined. The theory is similar to that of the Paschen-Back effect.

With the above methods the hyperfine interaction μH can be determined. Since the average hyperfine field H is not known it is determined by calibration with nuclear states with known g-factors, subject to the following assumption and conditions,

(1) Only *magnetic interaction* is assumed. This assumption is plausibe for the very large magnetic fields involved ($\sim 10^8$G) and has been shown to be valid by the Rehovot group.[5]

(2) *Same element*: the hyperfine field should be calibrated with the g-factor of a nucleus of the same element (*i.e.* an isotope) so that the electronic states will be identical.

(3) *Same velocity*: for the same reason the calibration should be made with ions having the same velocity distribution, since the velocity determines the amount of ionization and hence the electronic configuration. However, it is possible to relax condition (2) to include neighboring elements if the velocity distribution is adjusted to produce isoelectronic ions

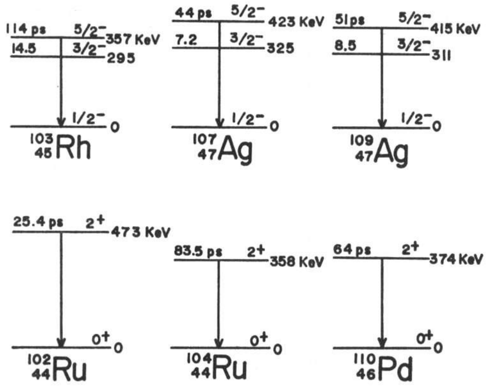

Fig. 2. Energy levels studied in this experiment. The three lower nuclei were used as standards to calibrate the hyperfine fields for the upper three nuclei.

i.e. ions having the same number of electrons. In this case the hyperfine field for nuclear charge Z can be adjusted precisely to that for Z' by theory.[6]

(4) *Same time*: the calibration should be made for the same perturbation time, since it has been found (see below) that the effective hyperfine field varies with time. This is accomplished by use of a stopper which limits the flight path of the recoils (see Fig. 1).

(5) *Same spin*: in principle the calibration should be made with a nuclear state of the same spin, since the hyperfine coupling depends on the relative magnitude of I (nuclear spin) and J (atomic spin). In practice J is known to be large, so that for small I the dependence on I is no large. In this work I has been limited to 3/2, 2, and 5/2.

This method may be called RIGUER (recoil-into-gas using empirical results).

With this method the hyperfine interactions of the nuclear states shown in Fig. 2 have been determined. The 2^+ levels in ${}^{102}_{44}$Ru, ${}^{104}_{44}$Ru, and ${}^{110}_{46}$Pd were used as standards; the g-factors for these levels are,[7,8]

$$g({}^{102}\text{Ru, 473 keV, 25.4 psec}) = 0.40 \pm 0.07$$
$$g({}^{104}\text{Ru, 358 keV, 83.5 psec}) = 0.30 \pm 0.04$$
$$g({}^{110}\text{Pd, 374 keV, 64 psec}) = 0.25 \pm 0.03 \,.$$

A typical sequence of curves of perturbation vs gas pressure is shown in Figs. 3 and 4. Figure 3 shows the curves for ^{107}Ag for free recoil, and Fig. 4 the curves with the stopper set at a distance corresponding to about 16 psec.

The data were analyzed with the AP theory to give values of gH. The results of many runs averaged together are shown in Fig. 5.

It is apparent that the hyperfine field strength $\bar{H}$ averaged over a perturbation time of 16 psec is larger than the field strength averaged over the lifetimes of the longer-lived $5/2^-$ states in unrestricted recoil by a factor $\bar{H}$ (16 psec)/$\bar{H}$ (44, 51, 114 psec) $= 1.45 \pm 0.15$. Thus, all the hyperfine fields used in this work were either measured for the short travel time ($\sim$ 16 psec) or corrected to it by the empirical relation given above.

The final results of the analysis are given in Table I and compared with the predictions of the weak-coupling, core-excited model.[9]

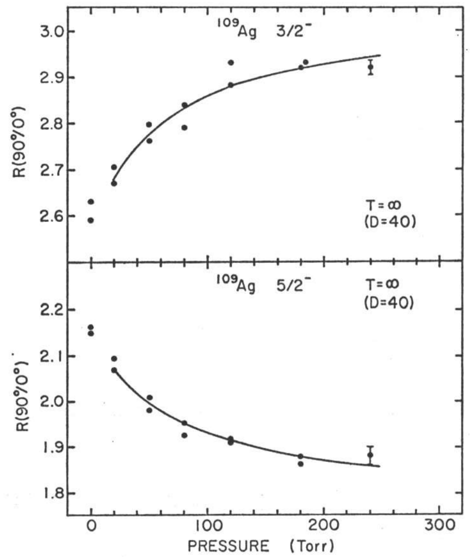

Fig. 3. The ratio of counts at 90° and 0° vs pressure of helium gas for states in ^{109}Ag for free recoil (stopper distance D = 1.0 mm).

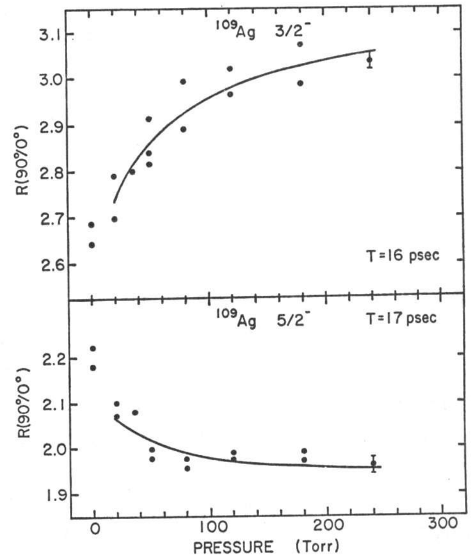

Fig. 4. The ratio of counts at 90° and 0° vs pressure of heluim gas at a stopper distance corresponding to average times shown.

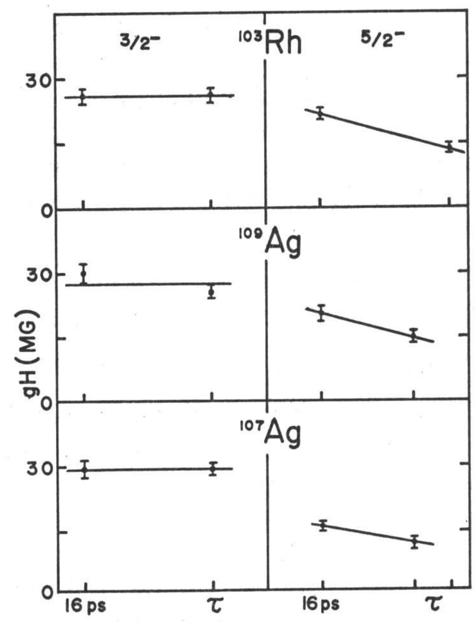

Fig. 5. Summary of the results. The points are averages of many runs. Those labeled τ are for free recoil; those at 16ps are for a stopper distance corresponding to this average time.

In the core-excited model the $5/2^-$ and $3/2^-$ states are formed by weakly coupling a $p_{1/2}$ proton to the 2^+ level of the core, as shown in Fig. 6. The g-factors are given simply by

Table I. Experimental values and predictions of the core-excitation theory.

Nucleus	Level	E_x keV	τ psec	g exp.	g theory	$g(3/2^-)/g(5/2^-)$ exp.	$g(3/2^-)/g(5/2^-)$ theory
^{103}Rh	$3/2^-$	295	14.5	0.47 ± 0.14	0.51		
	$5/2^-$	357	114	0.38 ± 0.13	0.28	1.22 ± 0.18	1.8
^{107}Ag	$3/2^-$	325	7.2	0.41 ± 0.14	0.53		
	$5/2^-$	423	44	0.35 ± 0.13	0.27	1.16 ± 0.29	1.9
^{109}Ag	$3/2^-$	311	8.5	0.45 ± 0.15	0.45		
	$5/2^-$	415	51	0.27 ± 0.09	0.21	1.66 ± 0.33	2.1

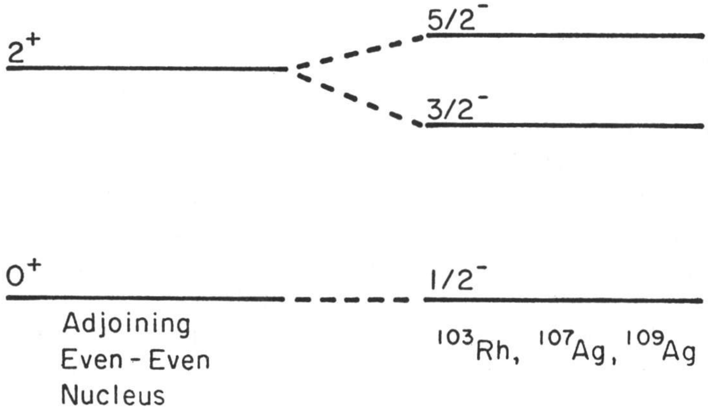

Fig. 6. The weak-coupling, core-excited model applied to ^{103}Rh, ^{107}Ag, and ^{109}Ag.

$$g_{5/2^-} = \frac{4}{5} g_{\text{core}} + g_{\text{p}}$$

$$g_{3/2^-} = \frac{6}{5} g_{\text{core}} - g_{\text{p}} \, .$$

It can be seen in Table I that for the g-factors the agreement of this model is quite good, *i.e.* within the experimental error in each case. However, it should be noted that there is a systematic difference in the comparison which shows up in the ratio of the g-factors. It will be interesting to see if admixtures of single-particle transitions can explain this systematic trend.

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Discussion

H. J. LEISI (ETH, Zürich): I would like to ask you to summarize the evidence for neglecting the quadrupole interaction in your work.

HANNA: I could do this, but I would prefer that Prof. Goldring do it since his group has provided the most convincing evidence.

G. GOLDRING (Weizmann Institute): The evidence for the absence of an E2 perturbation comes from direct, detailed angular distribution measurements which were found to exhibit, to high accuracy, a pure M1 perturbation pattern, even in cases involving nuclear levels with very large quadrupole moments. Such measurements are fairly independent of any details of the mechanism of perturbation other than the multipole character.

LEISI: It seems to me that the magnetic and the electric hyperfine interaction have to be added coherently. To my knowledge all evidence for neglecting the quadrupole interaction is based on an incoherent addition of magnetic and quadrupole effects.

GOLDRING: I don't think this applies to the statement I just made. It is true that it would be quite difficult to disentangle the two types of perturbation if one were faced with an intermediate situation. But if you have a situation, such as this one, where the measurements follow exactly the predicted M1 pattern, then you can conclude that there is no electric quadrupole interaction present, and this is independent of any other assumption.

D. A. SHIRLEY (Univ. of Calif., Berkeley): I believe that the Rehovoth group would contend that the good agreement of their G_2 vs G_4 curves with pure M1 perturbation would rule out sizable quadrupole effects even though the magnetic and quadrupole interactions combine coherently.

HANNA: Yes. Also, I would like to add that we are dealing with internal magnetic fields of the order of 50 MG. These produce very large perturbations of short-lived states as you have seen in the work I presented. By comparison, the quadrupole perturbations of short-lived states observed in implantation experiments are very small.

LEISI: In free atoms you can have appreciable quadrupole effects.

HANNA: Yes, of course, it requires an experimental test, such as the one Goldring has carried out.

L. ZAMICK (Rutgers Univ.): I would like to report that at Rutgers-Bell, Hubler, Murnick and Kugel measured the magnetic moment of the 2^+ state of ^{54}Fe, using the transient field technique, and obtained a value $g = 1.43 \pm 0.28$. This is in reasonable agreement with the $f_{7/2}^{-2}$ model.

HANNA: Yes, I am aware of that measurement. We have also been applying our method to this state, but the interpretation of the results is very difficult because of the very short lifetime which is about 1 ps. Our best analysis at present leads to a shorter lifetime for the 2^+ state of ^{54}Fe than given by Murnick *et al.*