CRITIQUE OF THE METHOD OF MEASUREMENT OF MAGNETIC MOMENTS OF NUCLEI EMBEDDED IN FERROMAGNETIC FOILS

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Anomalous magnetic fields have been found to exist at the sites of nuclei embedded, by recoil from Coulomb excitation, into iron and nickel foils, of such a nature that for considerable time intervals the large magnetic fields at the stopped nuclei are not parallel to the external magnetic fields. The reliability of this method of measuring nuclear g factors is therefore in considerable doubt. A model of the magnetic-field distribution is presented, but the mechanism which produces this distribution is not understood in detail.

Magnetic moments of short-lived excited states of a variety of nuclei have recently been measured[1-4] by embedding the excited nuclei in ferromagnetic media and observing the precession of the angular distribution of the γ rays from their decay. The excitation of the nuclei has been produced by Coulomb excitation with backscattered oxygen ions, utilizing the recoil from the reaction to drive the excited nucleus into the magnetic foil.[5] The foils have been magnetized by an external field perpendicular to the beam direction and to the plane in which the γ-ray distribution is measured. (We refer to such measurements as transverse field cases.) Magnetic fields of up to several hundred kilogauss have been found to be present at the sites of the excited nuclei embedded in Fe or Ni foils.

In order to extract the magnetic moments from the integral precession measurements, several apparently reasonable, but experimentally unverified, assumptions regarding the field acting on the embedded nuclei have been made. The experiment reported in this Letter indicates that at least some of these assumptions are not valid.

The assumptions involved in the analysis of previous experiments are as follows. The magnetic field at the embedded nucleus (1) becomes stationary in value and direction in less than several picoseconds after excitation, (2) it is parallel to the external field applied in the plane of the host foil, and (3) it has approximately the same magnitude for all embedded nuclei. It has also been assumed (and experimentally verified for Cu foils) that the quadrupole perturbations are small. If these assumptions hold, then the measured perturbation is purely due to a simple precession of the nuclear spin about the magnetic axis.

If assumption (2) listed above is correct, then it can be shown that the emission of γ rays into a cone whose axis is parallel to the applied magnetic field must be independent of the value of the magnetic field, the g factor of the excited state, or the orientation of the magnetic field relative to the Coulomb excitation direction. In other words, the γ-ray angular distribution measured with the host magnetic field pointing always toward the movable counter must be completely unperturbed. (We refer to these measurements as longitudinal field cases.) We have performed such measurements on Nd^{148} (2^+ state; $E_\gamma = 300$ keV; $\tau = 0.168 \pm 0.005$ nsec) and on W^{186} (2^+ state; $E_\gamma = 122$ keV; $\tau = 1.46 \pm 0.06$ nsec) and find in both cases that the distribution is considerably perturbed. Therefore, one or more of the assumptions mentioned above is incorrect.

Figure 1 shows a schematic drawing of the target, foil, and magnet assumbly for these measurements. The assembly can be rotated about an axis perpendicular to the beam direction in such a manner that the magnetic field

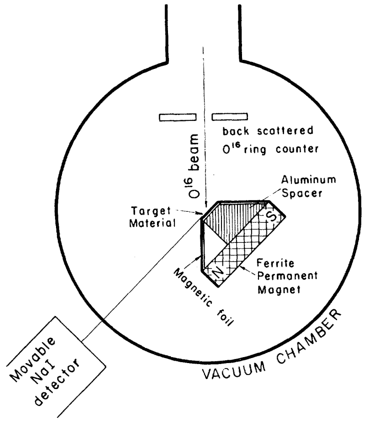

FIG. 1. Schematic drawing of magnet assembly and counters for the longitudinal field measurements. The ferromagnetic foil is brought to saturation by the permanent magnet. It is supported by a light aluminum frame. The target material is vacuum evaporated on the foil. The magnet can be rotated about the beam spot.

in the region of the beam spot can point toward the γ-ray counter. The targets were bombarded by a 32.4-MeV O^{16} beam from the tandem Van de Graaff. γ-ray spectra were observed with a 3-in.×3 in. NaI detector in coincidence with backscattered O^{16} ions which were detected in a ring-type surface-barrier detector. In addition to the distributions obtained from targets on Fe and Ni foils, targets deposited on Cu foils were also measured.[6] These serve as a calibration for the small effects of γ-ray scattering from the magnet holder, etc. The considerable perturbations observed in the longitudinal geometry are evidenced by the data shown in Fig. 2(a). Because of the geometric difficulties of rotation of the magnet assembly and the restrictions of the ring counter, it was only possible to measure the distributions over the limited angular range shown.

Extensive experimental tests were performed to verify the interpretation of the data. The magnet assembly was reoriented to produce a transverse field, and in this geometry, rotated angular distributions essentially identical to the patterns of Refs. 2 and 3 were obtained. Magnetic-induction measurements of the foil in situ confirmed that the field in the foil was very close to its saturation value. Reduction of the evaporated target thickness had no effect on the results. To test the possibility of longer magnetic relaxation times than expected from solid-state investigations, measurements were performed with the targets close to liquid-nitrogen temperature. Neither the rotation angles observed in the transverse field nor the attentuation observed in the longitudinal field were significantly affected by the lower temperature.

The data for the longitudinal field can be characterized by an average attenuation coefficient $\bar{G}$.[7] The values $\bar{G}$ as a function of the approximate values of $\omega\tau$ as derived below are shown in Fig. 2(b). The smooth behavior of $\bar{G}$ with $\omega\tau$ (and not with τ) suggests very strongly that the perturbation observed in the longitudinal geometry is purely of magnetic origin. In addition, the observed attenuations in the longitudinal case cannot be ascribed to quadrupole fields since this would be completely inconsistent with the large anisotropy and rotations observed in the transverse case, and also would require an unusually large value of the quadrupole field.

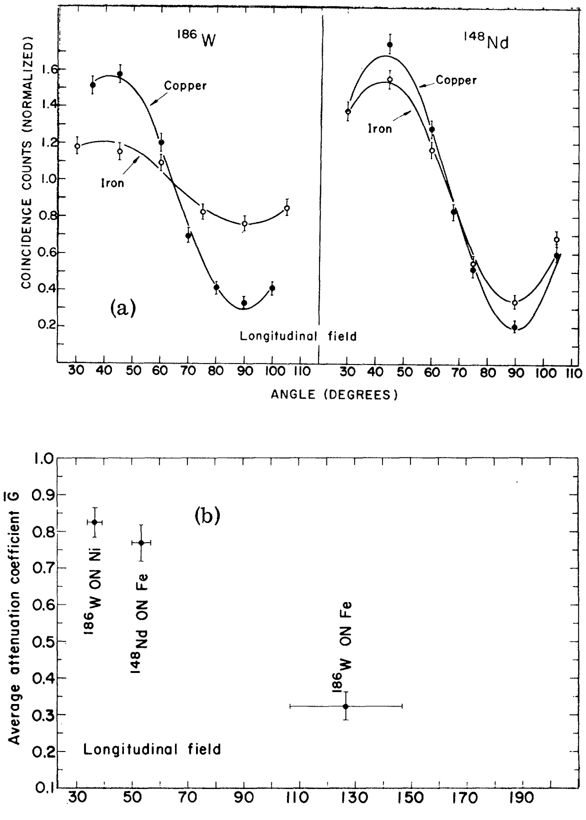

FIG. 2. (a) Angular distributions for W^{186} and Nd^{148} in longitudinal field geometry. Distributions obtained with Cu foil on same holder are shown for comparison. (b) Average (Ref. 7) attenuation coefficient $\bar{G}$ vs $\omega\tau$.

We have also measured the angular distributions for Nd^{148} and W^{186} in an unmagnetized ferromagnetic sample: Nd in soft iron and W in nickel. In these cases the attenuated distributions are presumably due to a random, static magnetic perturbation. Values of $\omega\tau$ derived[8] from these data are significantly larger than those obtained from conventional analysis of the transverse-field data.

In addition to these measurements there have been g-factor determinations reported for other W isotopes[2,9] and Pt isotopes[4] both by the Coulomb-excitation method and by Mössbauer techniques using dilute solutions of the relevant isotopes in ferromagnetic media. It has been reported in these cases that the effective magnetic fields at the recoils as derived from the transverse rotation measurements are considerably (by 20 to 30%) smaller than those of the Mössbauer magnetic-splitting experiments. No satisfactory explanation has been given for this discrepancy.

We have attempted to find a model to explain all the results presented. A simple model which involves only the relaxation of assumption 2 above appears to fit all of the available data. Assume that the excited nuclei, following embedding in the ferromagnetic foil, experience a constant magnetic field H which does not lie along the applied field direction but rather lies along the generating vectors of a cone making a polar angle Θ with the applied field direction. The longitudinal and transverse γ-ray angular distributions are then given by

$$W_{\text{long}}(\theta)=\textstyle\sum_k A_k G_k P_k(\cos\theta);$$

$$G_k=\frac{4\pi}{2k+1}\sum_u \frac{|Y_k^{\mu}(\Theta,0)|^2}{1+(\mu\omega\tau)^2},$$

$$W_{\text{trans}}(\theta)=4\pi\sum_{k\mu\mu'}\frac{A_k}{2k+1}|Y_k^{\mu'}(\tfrac{1}{2}\pi,0)|^2$$

$$\times\frac{d_{\mu'\mu}^{k}(\Theta)^2}{[1+(\mu\omega\tau)^2]^{1/2}}\cos(\mu'\theta-\mu\varphi_\mu), \quad (1)$$

where $\tan(\mu\varphi_\mu)\equiv\mu\omega\tau$ and $d_{\mu'\mu}^{k}$ is the rotation matrix for rotations about the y axis. A_k are the coefficients of the unperturbed distribution.

Least-squares fits of the data by the functions (1) were performed for the combined sets of longitudinal and transverse field data for each of the three cases measured. For each set a clear and reasonable minimum appears in χ^2 for a single set of parameters Θ and $\omega\tau$ which fit both the longitudinal and transverse data. The values of Θ and the internal field $H=(\omega\tau)\hbar/g\mu\tau$, derived[10] from $\omega\tau$, are given in Table I. Curves showing these fits to the data are given in Fig. 3. The values of H derived in this way are between 20 and 30% larger than those obtained from conventional analysis of the transverse data alone. A more reasonable physical model might not require that the magnetic field make a unique angle Θ with the applied field.

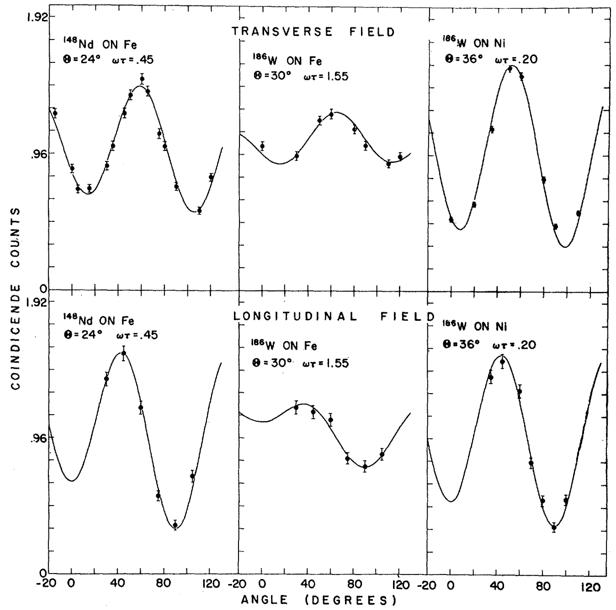

FIG. 3. Data and least-squares fits of longitudinal and transverse field data using "conical field" model [Eqs. (1)]. The data for the transverse field are from Refs. 2 and 3. The parameters $\omega\tau$ and Θ correspond to the values given in Table I.

Good fits to all the data have also been obtained assuming an angular spread of Θ with the applied field. Good fits to all the data have also been obtained assuming an angular spread of Θ with a distribution function $\exp(-\Theta/\Theta_m)\sin\Theta$. For this "smeared-cone" model the least-squares fits yield values of the mean angle Θ_m which are slightly larger than the single-cone hypothesis. The values of $\omega\tau$ are essentially unaffected. The values of $\omega\tau$ derived from the conical field models are the same as those obtained from the random-field data. This model also provides an explanation for the discrepancy in $\omega\tau$ values derived from the recoil experiments and the Mössbauer work with annealed samples.

The distortion of the field directions observed here may be a result of the method of deposition of the recoils, or, perhaps more likely,

Table I. Derived values of H_{int} and cone angle Θ.

Nucleus	Matrix	Homogeneous field[a] H (kG)	Conical field Θ (deg)	Conical field H (kG)	Random field H (kG)	Mössbauer field H (kG)
^{186}W	Ni	−64 ± 5	36 ± 2	−80 ± 16	±87 ± 12	±90 ± 25
^{186}W	Fe	−470 ± 36	30 ± 6	−620 ± 110		±700 ± 15
^{148}Nd	Fe	1900 ± 160	24 ± 6	2400 ± 260	±2150 ± 90	

[a] Ref. 10.

it is due to a suppression of the alignment of the field domains due to a not-inconsequential equilibrium concentration of oxygen ions from the exciting beam which load the foil in the critical region of deposition. Not enough is known regarding radiation damage of magnetic properties from oxygen bombardment to make a good quantitative estimate of these effects.

We have reanalyzed some of the recently published g-factor experiments using the "conical-field" model. Our main conclusion is that in all cases the old values of g are too low by between 15 and 30%. Relative g-factor measurements for isotopes of a given chemical species are probably affected by less than 20%. In particular, we have reanalyzed the data on g factors of the 4^+ states of W nuclei[2] and the 2^+ states of Nd^{144} and Nd^{146} [3] using the "conical-field" model. In these cases the field calibration was performed by measurements of the rotation of the transverse distributions of long-lived states. The result of this new analysis for the short-lived states is that the published g factors of the short-lived states should all be increased by about 15%. These statements depend critically on the assumptions (1) and (3) listed above which have not been verified with any accuracy and on the assumption that the average cone angle Θ is not critically dependent on the chemical nature and lifetime of the recoil. Of course, as long as the mechanism producing the "conical-field" distribution is not clearly understood, all g-factor experiments with recoil technique must be considered suspect.

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[2] P. Gilad, G. Goldring, R. Herber, and R. Kalish, Nucl. Phys. A91, 633 (1967).

[3] I. Ben-Zvi, P. Gilad, G. Goldring, R. Herber, and R. Kalish, Nucl. Phys. A96, 138 (1967).

[4] R. Kalish, private communication.

[5] The recoil energies are initially of the order of 10 MeV. They are expected to stop in the foil in times of order 10^{-12} sec at depths of approximately 1 μ.

[6] ^{148}Nd on Cu has been found in a recent measurement to yield a completely unperturbed distribution. The slight perturbation in ^{186}W on Cu has been taken into account in the analysis of the data in an approximate manner.

[7] For the particular case of Coulomb excitation with backscattered ions, of a 2^+ state, the unrotated γ-ray angular distribution is given by $W(\theta)=1+(5/7)b_2G_2 \times P_2(\cos\theta)-(12/7)b_4G_4P_4(\cos\theta)$. The angle θ is with reference to the beam direction, the quantities b_2 and b_4 are geometric (finite detector solid angle) correction factors, and G_2, G_4 the attenuation coefficients. We define an average attenuation coefficient $\overline{G}$ by $\overline{G}\equiv(5b_2G_2+9b_4G_4)(5b_2+9b_4)^{-1}$. When distributions are obtained over only a small range of angles, the quantity $\overline{G}$ can be determined with much higher accuracy than the individual G_2, G_4. Least-squares fits of the longitudinal data for G_2 and G_4 show in any case that $G_2>G_4$.

[8] The formulas for this case are given by E. Matthias, S. Rosenblum, and D. Shirley, Phys. Rev. Letters 14, 46 (1965).

[9] E. Kankeleit, Bull. Am. Phys. Soc. 10, 65 (1965), and private communication.

[10] In Table I, the values of H_{int} are presented in order to enable a direct comparison with the Mössbauer work. H_{int} is derived from the corresponding $\omega\tau$ values using the nuclear g factors obtained from precession measurements in an external magnetic field as given in Refs. 2 and 3. The g factors used are as follows: $g_{\mathrm{Nd}}=0.24$ and $g_{\mathrm{W}}=0.35$. The errors in the values of the g factors have not been included in the errors in H_{int} since the comparison of the different model calculations are independent of this error. However, in comparison with the Mössbauer results and for determination of the absolute values of H_{int} the errors in the g factors (±10% for W^{186} and ±20% for Nd^{148}) should be included.