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g Factor of the 50-keV $\frac{3}{2}^-$ State in ^{223}Ra and the Internal Magnetic Fields at Ra Nuclei in Ferromagnets*

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The γ-γ perturbed angular correlation of the 236–50-keV cascade in ^{223}Ra has been investigated, yielding $g(\frac{3}{2}^-,\ 50\ \text{keV}) = +0.28 \pm 0.04$. The magnetic hyperfine fields experienced by Ra nuclei embedded in Ni, Co, and Fe lattices were found to be -30 ± 10, -80 ± 16, and -105 ± 20 kOe, respectively.

The hyperfine magnetic fields at the sites of impurity atoms diffused in ferromagnetic hosts have been observed to exhibit a frequent change of sign as a function of the atomic number of the impurity. This behavior can be qualitatively understood from the electron configuration of the impurity. From systematics, the hyperfine magnetic fields on "5*d*" impurity atoms diffused in Fe lattice should have a behavior similar to the fields observed on "4*d*" elements in the same host. In particular, the field on Ba in Fe is small,[1] $H_{\text{int}}(\text{Ba}\,Fe) = 0 \pm 100$ kOe and since Ra is the "5*d*" counterpart of the "4*d*" Ba (both terminate their respective series), a similar result for Ra seems likely. In this paper we describe the results of measurements of the hyperfine magnetic fields acting on radium nuclei in Fe, Co, and Ni hosts. As a probe in this field measurement, the nuclear magnetic moment of the first $\frac{3}{2}^-$ state of ^{223}Ra was used. In a preceding experiment, this magnetic moment was determined.

The experiments have been performed with the perturbed-angular-correlation (PAC) method. The levels of ^{223}Ra are populated by α decay of ^{227}Th, which in turn is fed by β decay of the 22-yr ^{227}Ac. From the partial level diagram of ^{223}Ra shown in Fig. 1, it is clear that the measurement of the $\frac{3}{2}^-$ state requires the use of Ge(Li) spectrometers. The apparatus is the same as that described in the work of Levanoi, Zawislak, and Cook,[2] but two 5-cm^3 planar Ge(Li) detectors were used. Figure 2 shows the low-energy spectrum of ^{227}Ac and daughters, with the γ lines of interest (50 and 236 keV), which in our experiment could be well resolved.

The γ-γ sequence $\frac{3}{2}^+(236\ \text{keV})\frac{3}{2}^-(50\ \text{keV})\frac{1}{2}^+$ was investigated. Using a liquid source of carrier-free ^{227}Ac activity in a dilute solution of HNO_3, the angular-correlation function for this cascade was determined, yielding, after solid-angle correction, coefficients $A_2 = -0.205 \pm 0.005$, and $A_4 = 0$. This result is in agreement with a previous measurement,[3] and also in agreement with the theoretical coefficients $A_2 = -0.20$ and $A_4 = 0$ assuming that both transitions are pure electric dipoles in accordance with conversion-electron data. These results also indicate that time-dependent quadrupole interactions, which could attenuate the angular-correlation function during the relatively long lifetime of the intermediate state, are negligible.

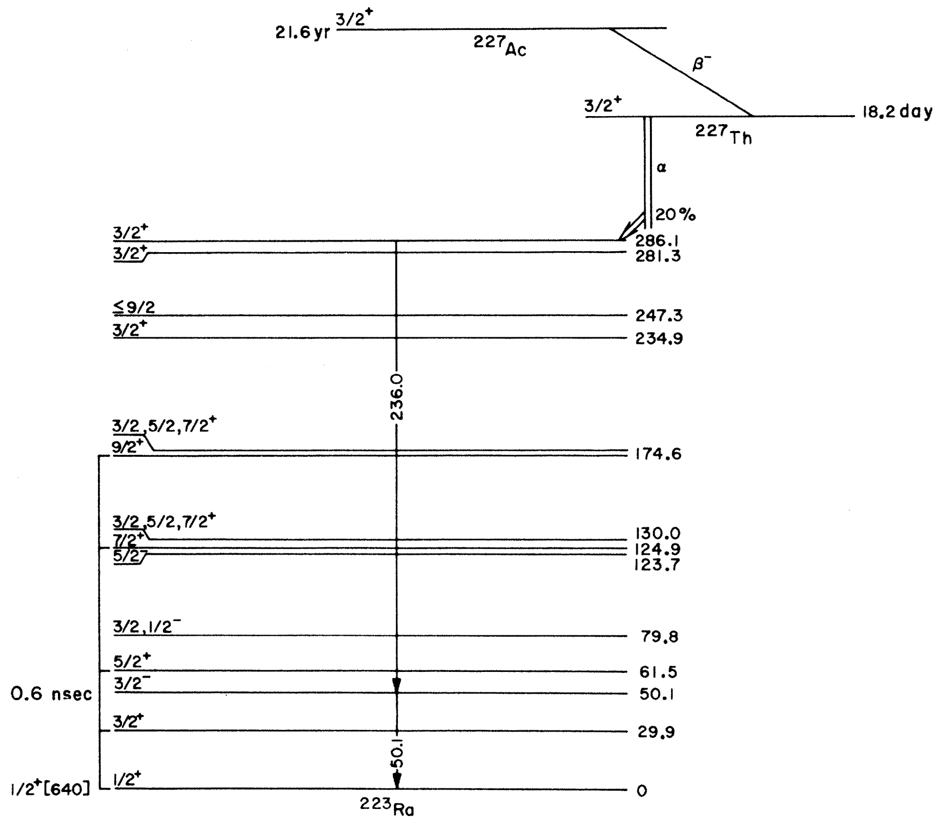

FIG. 1. Partial level diagram of ^{223}Ra.

The g factor of the level at 50 keV was measured in an external magnetic field of 28 kOe. The liquid source was placed between the poles of the magnet and, in order to increase the coincidence rate, both detectors were moved closer to the source. In this geometry we obtained angular-correlation coefficients $A_2 = -0.120 \pm 0.005$ and $A_4 = 0$ (uncorrected for geometry). The mean precession angle $\omega\tau = 34 \pm 3$ mrad of the 50-keV state was deduced from the ratio

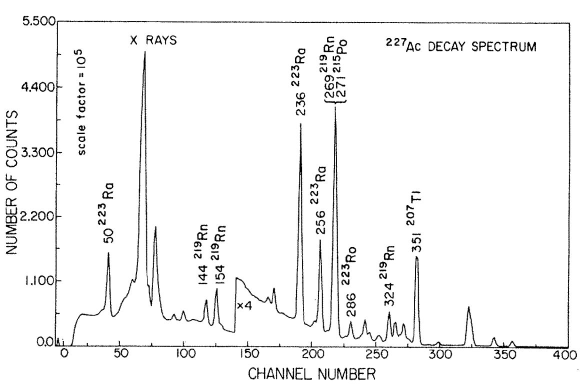

FIG. 2. Low-energy γ spectrum of ^{227}Ac and daughters with a 5-cm^3 planar Ge(Li) detector.

$$R(\theta, H) = [W(\theta, +H) - W(\theta, -H)]/[W(\theta, +H) + W(\theta, -H)]$$
$$= (1/W)(dW/d\theta)\omega\tau + O[(\omega\tau)^3]$$

measured at 135 and 225°. This value of $\omega\tau$ with a mean lifetime[4] $\tau(50 \text{ keV}) = 0.91 \pm 0.10$ nsec yields

$$g(50 \text{ keV}, \tfrac{3}{2}^-) = +0.28 \pm 0.04.$$

Alloys of Ac with the ferromagnets were prepared by depositing the carrier-free ^{227}Ac activity in dilute HNO_3 on ~80 mg of powder of pure Fe, Co, and Ni metals. The mixtures were washed with water, dried, and reduced in hydrogen. The reduced powders were coined into small cylinders under a pressure of ~10^3 atm. In a second step, the cylinders were rolled into thin foils (~0.3-mm thickness) and annealed for 5 h at 800°C. All alloys had less than 0.01 at.% of Ac.

The metallic foil sources, shaped into cylindrical shells, were polarized by an external magnetic field; the Fe and Ni alloys were aligned with a field of 3 kOe, and Co with 18 kOe. The integral-reverse-field technique for the PAC method was employed in the measurement of the Ni source. The Fe and Co sources, displaying larger mean precession angles, were investigated by both the integral-reverse-field and the integral-rotation methods. The angular-correlation coefficients (uncorrected for geometry) were found to be $A_2 = -0.10 \pm 0.005$, -0.08 ± 0.004, and -0.07 ± 0.004 for Ni, Co, and Fe, respectively, while $A_4 = 0$ (within experimental error) in all cases. These should be compared with the value $A_2 = -0.12 \pm 0.005$ obtained for the liquid source in the same geometry. The attenuation of the angular correlation in the metallic sources with respect to the correlation in the liquid source has been attributed to scattering of the low-energy (50 keV) γ ray in the source. It was found that the contributions due to elastic and inelastic scattering of up to 90° with energy loss of less than 5 keV are sizable at the present γ energy, source thickness, and geometry. The different attenuations in the three metallic sources are due to variations in their thicknesses. Additional attenuations due to hyperfine interactions cannot entirely be excluded. However, it appears that the attenuations resulting from static and time-dependent quadrupole interactions are small, both in the liquid and metallic sources.

The results of the integral-reverse-field measurement performed at $\theta = 135$ and 225° are: $\omega\tau(\mathrm{Ra}Fe) = -120 \pm 18$ mrad, $\omega\tau(\mathrm{Ra}Co) = -100 \pm 30$ mrad, and $\omega\tau(\mathrm{Ra}Ni) = -35 \pm 10$ mrad. The integral-rotation measurements yielded directly: $\omega\tau(\mathrm{Ra}Fe) = -150 \pm 35$ mrad and $\omega\tau(\mathrm{Ra}Co) = -70 \pm 15$ mrad, in agreement within errors with the values obtained by the reverse-field technique. The table shows our results, where $\omega\tau$ for Fe and Co hosts is the weighted average of the values obtained using the two different techniques. The quoted hyperfine magnetic fields in the last column of the table have been corrected for the external aligning field.

The negative value of $H_{\mathrm{int}}(\mathrm{Ra}Fe)$ shows that the change of sign on the field occurs between radon[5] ($Z = 86$) and radium ($Z = 88$), and also indicates that the hyperfine magnetic fields on "5*d*" impurity atoms diffused in an Fe lattice have a behavior similar to the fields observed on "4*d*" elements in the same host. The hyperfine fields in the three ferromagnets are found to be proportional to the magnetic moments of the host metals, in agreement with results obtained for most of diamagnetic impurities diffused in the same matrices.

TABLE I. Mean precession angle $\omega\tau$ obtained from the counting ratio $R(\theta)$, and hyperfine fields deduced using the *g* factor and lifetime of the 50-keV state in ^{223}Ra (see text).

	$\omega\tau$ (mrad)	H_{int} (kOe)
Ra*Fe*	-125 ± 16	-105 ± 20
Ra*Co*	-76 ± 13	-80 ± 16
Ra*Ni*	-35 ± 10	-30 ± 10

Ansaldo, Grodzins, and Kalish[5] recently measured the hyperfine magnetic field on ^{224}Ra in Fe observing the α-γ angular correlation from a thin ^{228}Th source deposited on a magnetically polarized iron foil. A value $H_{\mathrm{int}}(^{224}\mathrm{Ra}Fe) = -230$ kOe was reported by the authors, assuming from theory a *g* factor +0.15 for the first 2^+ state in ^{224}Ra. Our result of $H_{\mathrm{int}}(^{223}\mathrm{Ra}Fe) = -105 \pm 20$ kOe agrees in sign, but not in magnitude, with the above value. Clearly an experimental determination of the *g* factor of the 2^+ state in ^{224}Ra would be highly desirable in order to learn if measurements of hyperfine fields by α-γ and γ-γ conduce to the same results. A collective *g* factor of ~0.3 in this region would also resolve this discrepancy.

Since the levels of ^{223}Ra are directly populated by the α decay of ^{227}Th, it must be kept in mind that the recoil of the α particles can leave the Ra atoms in either substitutional or interstitial positions. It is therefore not possible to state whether our field values pertain to substitutional or interstitial sites, or to an average of both.

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