HYPERFINE FIELDS AT Ca^{42} IN FERROMAGNETIC METALS AND THE g FACTOR OF THE 3.19-MeV 6^+ STATE*

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The hyperfine fields at Ca in ferromagnetic metals have been studied by time-differential measurements on the 3.19-MeV 6^+ state in Ca^{42}. The observed hyperfine field in Fe was $H_{hf} = -100 \pm 9$ kG; preliminary results in Co indicated $H_{hf} = -70 \pm 15$ kG and in Ni suggested $|H_{hf}| < 30$ kG. These results are in disagreement with predictions by Balabanov and Delyagin. A time-integral measurement in an external magnetic field yielded $g(6^+) = -0.42 \pm 0.03$. The mean lifetime of the 6^+ state was remeasured to be $\tau = 7.65 \pm 0.23$ nsec.

Balabanov and Delyagin[1] have shown that the experimental hyperfine fields at nuclei of impurity atoms in ferromagnetic metals (Fe, Co, Ni) can be well described by a simple equation. Their interpretation of this equation is that the main contribution to the hyperfine field arises from polarized electrons in the filled shells of the impurity atom and that this polarization is produced by two opposing mechanisms. Their equation, which was applied to atomic periods 4, 5, and 6, predicts a large positive hyperfine field at the beginning and end of the atomic periods and negative values in the middle. In this Letter we report on an experimental measurement of the hyperfine field at Ca^{42} implanted in Fe which yields a value of -100 ± 9 kG rather than the $\sim+300$ kG predicted for Ca in Fe. Preliminary measurements for Ca^{42} implanted in Co and Ni have also been made; the observed hyperfine fields in Co and Ni are consistent with the Fe result in that they are proportional to the atomic magnetic moment of the ferromagnetic host and also do not agree with the prediction. These hyperfine fields are of interest to the above theory as few experimental results are available at the beginning of the fourth atomic period. In addition, the Ca hyperfine fields are of particular importance for nuclear studies of magnetic properties of short-lived excited states in the various Ca nuclei. These isotopes, of which six are stable including two with doubly closed shells, offer an abundance of nuclear information.

The hyperfine field at Ca^{42} in Fe was measured by a time-differential perturbed angular correlation (PAC) technique. The 3.19-MeV 6^+ state in Ca^{42} was excited by the reaction $K^{39}(\alpha,p)Ca^{42}$ with a 10.03-MeV α beam from the model FN tandem at Stony Brook. The target consisted of 610 μg/cm^2 of natural KI evaporated onto a 7.5-μm Fe backing which was saturated by an external magnetic field of 1.35 kG. Backscattered protons were detected in an annular silicon detector, while the 438-keV decay γ's were detected in two 3.8×3.8-cm NaI crystals which were positioned at 45 and 135°. The prompt resolution function of the fast timing apparatus was ~800 psec full width at half-maximum. The measurement was carried out at room temperatures with the beam spot frequently shifted to avoid radiation damage.

Figure 1 shows the perturbed decay curves ob-

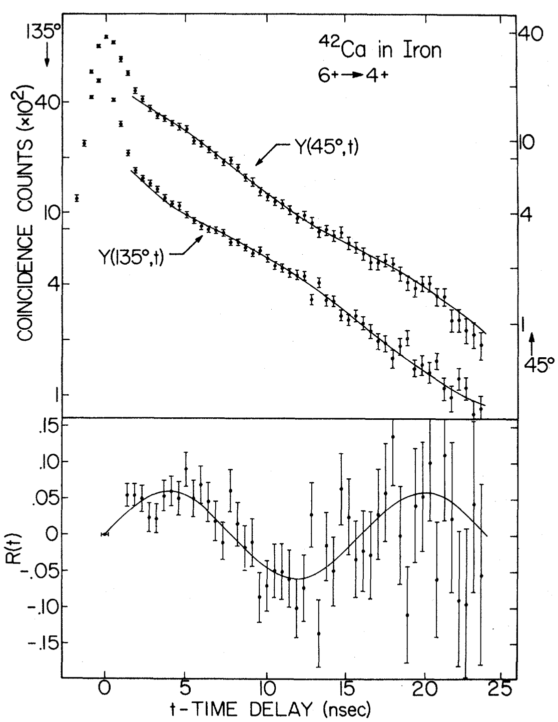

FIG. 1. The perturbed curves obtained from the p-γ fast timing circuit with NaI scintillators at 45 and 135° and an annular silicon detector at back angles. The bottom portion shows the experimental $R(t) = [Y(45°,t) - Y(135°,t)]/[Y(45°,t) + Y(135°,t)]$. The solid curves drawn through the data were generated from the least-squares fit of $R(t)$ by the function $R\sin(2\omega_L t)$.

tained from the p-γ fast-slow timing circuit. The data were analyzed by forming the ratios $R(t)=[Y(45°,t)-Y(135°,t)]/[Y(45°,t)+Y(135°,t)]$; a Fourier analysis and a least-squares sine fit of $R(t)$ were made. The experimental $R(t)$ and the theoretical fit are shown in the bottom part of Fig. 1. The resulting Larmor frequency $\omega_L = g\mu_n H/\hbar$ is $(0.198\pm0.012)\times10^9$ sec^{-1}. No additional frequencies of statistical significance were found in the Fourier analysis. The fitted amplitude implies an A_2 corrected for geometry of 0.080 ± 0.10; the A_4 was found to be small. The initial unperturbed angular correlation was measured under similar experimental conditions except for the use of a 75-μm Pt backing and was $A_2=0.39\pm0.03$; $A_4=-0.17\pm0.02$. The observed A_2 in Fe was only $(21\pm4)\%$ of the A_2 in Pt. The mean lifetime of the 6^+ state extracted from the time-differential data was $\tau=7.65\pm0.23$ nsec.

In order to obtain a hyperfine field from the observed Larmor frequency, the g factor of the 6^+ state was measured by a time-integral PAC method. The reaction $K^{39}(\alpha,p)Ca^{42}$ was used with a 75-μm Pt backing and a 7.9-MeV α beam. A singles angular distribution of the $6^+\to4^+$ γ's was measured with a 30-cm^3 Ge(Li) detector yielding a correlation of $A_2=0.32\pm0.04$, $A_4=-0.10\pm0.02$. An external field of 10.3 kG was applied; the shift in counting rate for field up and field down was observed with the Ge(Li) detector at 61.5°. For these measurements both particle detection and charge integration were used as monitors. Beam-bending corrections for the incoming He^+ ions have been made. In this manner the 6^+ g factor was measured to be -0.42 ± 0.03; this value yields a Fe hyperfine field at Ca^{42} of $H_{hf}=-100\pm9$ kG. Because the Ca^{42} 6^+ state is known to be a pure $(1f_{7/2})^2$ configuration,[2] the $g(6^+)$ is expected to equal $g(1f_{7/2})$ which is -0.4556 from the Ca^{41} NMR measurement.[3] If this precise g factor is used, assuming a $(1f_{7/2})^2$ 6^+ state, a more accurate hyperfine field $H_{hf}=-92\pm6$ kG is obtained.

The equation of Balabanov and Delyagin[1] describing the hyperfine fields is $H/\mu Z_0^{1.3}=-2.48+0.113(\nu-9)^2$, where μ is the magnetic moment of the ferromagnetic atom, Z_0 is the number of electrons in filled shells for the impurity atom, and ν is the total number of electrons in the outer shell of the impurity atom. The two mechanisms that polarize the electrons in the filled shells of the impurity atom are represented by the equation. Both mechanisms originate from the polarized electrons in the conduction band of the ferromagnetic metal: The first, which results in a positive hyperfine field, is a direct interaction with the electrons in the filled shells of the impurity atom; the second is an indirect interaction via the polarization of the electrons in the outer shell of the impurity atom. The latter mechanism results in a negative hyperfine field which depends on the total number of outer electrons. The parameters in the above equation, which were determined by a least-squares fit of experimental data for impurity atoms from atomic periods 4, 5, and 6, give a hyperfine field at Ca in Fe of $H_{hf}=+290$ kG. This predicted positive hyperfine field does not agree with the negative hyperfine field of $H_{hf}=-100\pm9$ kG observed for Ca^{42} in the present experiment. The explanation for this large discrepancy is not apparent at this time.

The measurements of Ca^{42} implanted in Co and Ni were performed in an identical manner to the measurements in Fe. A preliminary result for Co shows perturbations corresponding to a hyperfine field of -70 ± 15 kG with an anisotropy $A_2\sim0.2$ which was larger than that observed in Fe. For Ni, no perturbations with periods within the time range of the measurement were observed. With the time range limited to about 20 nsec, this measurement suggests that the absolute value of the hyperfine field in Ni is less than 30 kG. The Ca^{42} hyperfine-field results for Fe, Co, and Ni are thus consistent with a proportionality to their respective magnetic moments $\mu=2.2$, 1.7, and 0.6. The equation of Balabanov and Delyagin[1] predicts hyperfine fields at Ca of ~+220 and ~+80 kG in Co and Ni, respectively; these values, as for Fe, are not in agreement with the experimental values.

The reduction in anisotropy in the ferromagnetic metals as compared with Pt suggests the possibility of different types of stopping sites for Ca implanted in the ferromagnetic lattice. These different sites including the lattice sites might have hyperfine fields that correspond to precession frequencies outside the range of experimental sensitivity or to a distribution of frequencies. The present experiment was sensitive to a range of hyperfine fields of approximately 30-500 kG which covers the predicted fields for each of the ferromagnetic metals. Although no other fields were statistically identified in this range, the sensitivity to their observation is only proportional to the fractional population for a given field. Several hyperfine fields have been observed at implanted F^{19} in ferromagnetic metals.[4]

The above equation is not expected to predict complexities beyond that for normal lattice sites. The assumption has been made that the observed hyperfine fields originate at normal lattice sites; however, the experiment does not determine this fact.

Strong relaxation processes are a plausible explanation of the reduced alignment in ferromagnetic metals. In the present experiment, the reduction of alignment occurs in less than 2 nsec, but the alignment that remained in both Fe and Co did not appear to be relaxed in the following 20 nsec. A recent set of experiments[5] has shown that strong time-dependent quadrupole relaxation can be produced from radiation-induced vacancies. This radiation damage may occur in the ferromagnetic lattice with the implantation technique; however, for the unrelaxed alignment, it is not expected to alter the hyperfine field.

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INADEQUACIES IN A CONVENTIONAL DISTORTED-WAVE BORN-APPROXIMATION ANALYSIS OF (p,t) TRANSITIONS IN TITANIUM ISOTOPES AT $E_p = 27$ MeV†

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Some measurements of (p,t) differential cross sections are reported for which a conventional distorted-wave Born-approximation analysis does not work well, and where the findings suggest caution in the interpretation of (p,t) studies in the $A = 50$ mass region at a bombarding energy of about 27 MeV.

Differential cross sections in the reactions ^{50,48,46}Ti$(p,t)^{48,46,44}$Ti at $E_p = 27$ MeV were measured in the angular range $5° \leq \theta_L \leq 110°$. In attempting to analyze these with distorted-wave Born-approximation (DWBA) methods, it was found that even with the considerable flexibility which exists in these methods, the calculations do not reproduce the shapes of the angular distributions well. More significantly, both the shapes and magnitudes of the calculated angular distributions at forward angles are quite sensitive to the parameters of the calculations. The shape sensitivity at forward angles limits the possibility of exploiting the two-nucleon coherence in the testing of nuclear wave functions. Since these results may be of more general interest, a discussion which includes some representative data is given in this Letter.

The experiment was performed with the University of Colorado 1.3-m sector-focusing cyclotron and with solid-state detectors. Data at forward angles ($\theta \leq 25°$) were obtained by use of a quadrupole-lens spectrometer of a new design.[1] A full description of the experiment will be given in a future paper. Typical examples of angular distributions for transitions with $L = 0$, 2, and 4 to known states in the reaction ^{48}Ti$(p,t)^{46}$Ti are shown in Fig. 1. The incident beam energy and reaction Q values for these transitions are such that the outgoing tritons have energies near 15 MeV. Since extensive triton elastic-scattering data exist for this energy range, the choice of bombarding energies for the present study is favorable for a DWBA analysis. Also the full angular range covered by our data is desirable for an adequate assessment of the DWBA calculations. In a recent study[2] of the reaction ^{42,44}Ca(p,t) at 26.5 MeV some of the difficulties to be discussed were noted; however, since forward-angle data were not available, evaluation of the DWBA analysis was limited.

The three angular distributions displayed in Fig. 1 were used as primary test cases in the analysis. The sharp diffraction pattern observed for the $L = 0$ transition strongly suggests that